REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave Blank*)

2. REPORT DATE
8 July 1997

3. REPORT TYPE AND DATES COVERED
Final (27 Nov. 96 to 23 May 97)

4. TITLE AND SUBTITLE Development and application of an acoustic waveguide technology to in-process cure and in-service dynamic response monitoring of liquid molded composite armor smart structures.

5. FUNDING NUMBERS
Contract Number:
DAAL01-97-C-0047

Project Number:
97-R-9057

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8. PERFORMING ORGANIZATION REPORT NUMBER

97-010

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Army Research Laboratory
Aberdeen Proving Ground, MD 21005

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

19970711 024

13. ABSTRACT (*Maximum 200 words*) Report developed under SBIR contract: A multi-functional ultrasonic sensor has been developed for liquid molding composite materials under this SBIR program. The sensor can be used to monitor a) the flow of the resin during resin infusion, b) the cure of composite parts and structures during the cure process, and c) structural dynamic responses and damages after the part is placed in service. The sensor has a low profile and is embedded in the composites manufactured through processes such as Resin Transfer Molding (RTM) or Seemann Composites Resin Infusion Manufacturing Process (SCRIMP). This report describes the research performed under the contract. It discusses the sensor development, operation and implementation. Through experimental results, the sensor's sensitivity, capability and applications are also discussed. Special emphasis is placed on the application to cure monitoring of thick composites. The potential for the same sensor to be used as smart sensor is presented through detection and monitoring of impact induced damage to the composite parts.

14. SUBJECT TERMS SBIR report, Cure monitoring, wire waveguide, embedded sensor, smart structure, composite armor, liquid mold, dynamic response monitoring, ultrasonic transducer, RTM, SCRIMP.

15. NUMBER OF PAGES
43

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

DTIC QUALITY INSPECTED 3 REF D

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

XXSYS TECHNOLOGIES, INC.

CONTRACTED RESEARCH AND DEVELOPMENT REPORT

TO

DEPARTMENT OF THE ARMY

DEVELOPMENT AND APPLICATION OF AN ACOUSTIC WAVEGUIDE TECHNOLOGY TO IN-PROCESS CURE AND IN-SERVICE DYNAMIC RESPONSE MONITORING OF LIQUID MOLDED COMPOSITE ARMOR SMART STRUCTURES

(PROJECT NUMBER: 97-R-9057; CONTRACT NUMBER: DAAL01-97-C-0047)

SBIR PHASE I
FINAL REPORT

(For the period from November 27, 1996 through May 23, 1997)

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JULY 8, 1997

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PROJECT SUMMARY

Purpose

The goal of this program is to develop a rugged, low cost, dual-purpose, embedded ultrasonic sensor system that can be used for manufacturing process control and for in-service health monitoring of monocoque or hybrid liquid molded composite armor. Successfully developed, the sensor measurement system will monitor the flow/cure of the liquid molded structural parts during fabrication. With integrated sensors, this will achieve intelligent process control and ensure the composite armor is produced consistently and efficiently. After the parts are placed in service, the dual-purpose sensors will also be used as smart structure material sensors in a dynamic mode for damage detection or to provide input for active control of vibrational responses.

Description of Research

The method researched is based on ultrasonic wave propagation in a wire waveguide (WWG). The main focus was on development and demonstration of an embedded sensor that can: a) detect when resin flows to the sensor during resin infusion, b) determine when resin has reached cure in the curing process, and c) measure changes in vibrational responses of composite structures. Development and demonstration of the researched sensor technology and measurement system was accomplished through fabrication of liquid molded parts with multiple embedded sensors.

Research Results for Phase I

An ultrasonic sensor technology has been developed and its technical feasibility demonstrated. An effective low profile WWG sensor was developed that can be embedded in a composite part during fabrication. The sensor consists of small piezoelectric plates attached to a specially shaped stainless steel wire. Energy to and from the sensor is delivered through miniature coaxial cables. Successful experiments were conducted in neat resin, RTM mold, half-inch mold SCRIMP, and four-section large mold SCRIMP with thicknesses up to 2". Experiments were also performed to demonstrate the same sensor can be used to detect impact damages in composite parts. The experimental results are highly reproducible and the sensors are easy to fabricate and install. The sensor technology is potentially patentable. A complimentary data acquisition and analysis system was also developed. The goals set for this project were all successfully achieved.

Potential Applications

Success in this phase provides the basis for a comprehensive validation study in the actual composite armor manufacturing process. This Phase II effort would include application of the embedded sensor technology to a composite armor demonstration part by interfacing sensor-obtained flow/cure information to the liquid molding process. Subsequent in-service damage detection on the same part with the same sensor will also be demonstrated. Success in these demonstrations will lead to prototype development of multi-sensor measurement systems.

ACKNOWLEDGMENT

XXsys would like to acknowledge the contribution of Mr. Jerry Posakony of J-Tech Consulting, for his valuable assistance throughout this project, particularly in the development of the WWG sensors and the completion of the final report. In addition, XXsys would like to thank Mr. Shyang Liu for his valuable technical assistance in the design and fabrication of various parts needed for this project.

TABLE OF CONTENTS

I. INTRODUCTION AND SUMMARY OF ACCOMPLISHMENTS

Background

Over the last decade, liquid molding techniques have become increasingly popular for manufacturing of composite parts and structures. These techniques are often selected because of the ease of manufacturing automation and the ability to effectively and inexpensively produce large and complex parts and structures. Resin transfer molding (RTM) and Seemann's composite resin infusion molding process (SCRIMP) are two widely applied liquid molding techniques in both the military and civilian sectors.

Due to their many attractive characteristics, such as high strength and light weight, composites are being considered as alternatives for armor structures. Liquid molding techniques are typically used for fabrication of these monocoque or hybrid composite structures. These armor structures present unique challenges to the liquid molding process because some sections of the armor composites are thick (up to 4" for some heavy weight armors) and varying. Proper resin flow and cure in these applications are crucial to the quality of the composites and manufacturing consistency. As a result, it is highly desirable to have a sensor system that can obtain flow/cure information and use it to achieve intelligent system control during the composite manufacturing process.

There is also a strong need for in-service monitoring and assessment of the integrity, overall health, and damage on the composite structures resulting from normal use, impact or battles. In particular, a smart structure which has the capability to detect structural damage and degradation can be very valuable for ensuring continued integrity of the composite armor.

Therefore, a dual purpose sensor system that can be used both for in-process flow/cure measurement and in-service monitoring of the dynamic responses of the composite armor structure would be most desirable. Development of such a dual purpose sensor system is the focus of this project.

Phase I Objective and Description

Phase I of this research program is aimed at investigating and developing an ultrasonic method to: a) monitor the resin flow/cure of a liquid molding composite manufacturing process and b) measure the dynamic vibrational responses of the finished parts. The main emphasis is placed on demonstrating the technical feasibility of wire waveguide (WWG) sensor technology to RTM and SCRIMP liquid molding techniques.

Experimental studies were carried out with various sensor designs and configurations at a number of operating frequencies. Multiple experiments were conducted in which WWG sensors were embedded in the molded composite parts. These experiments included neat resin, RTM and SCRIMP with three different types of epoxy resins. Several design/testing iterations were made during the sensor development. The final version of the developed WWG sensor clearly provided timing information on the resin flow and cure. Vibration experimental results showed the same WWG sensor can in fact be used for vibration monitoring.

This project has been very successful. The technical feasibility of the dual purpose sensor was clearly demonstrated. The criteria for success outlined in the original proposal have all been met.

Description of Report

This report consists of four main sections in addition to the Project Summary. Section I gives a brief introduction and summary of accomplishments. Section II is the main body of the report detailing the research performed in this project. Section III provides an overall evalution of the technical feasibility in connection to the accomplishments achieved. Section IV concludes this report with an outline for anticipated research and development in Phase II.

Summary of Accomplishments

The accomplishments achieved in this project are summaried below:

Task 1: Sensor/transducer development - - An efficient, low profile WWG sensor was developed that is capable of monitoring the resin flow and cure of liquid molded composite parts. The sensor is less than 0.05" in thickness with a 0.5" x 2" footprint. It is constructed with two piezoelectric plates (one transmitter and one receiver) bonded to a specially shaped stainless steel wire. The sensor is typically operated at 350 kHz with excellent operating efficiency. The electric energy to and from the piezoelectric plates is delivered through thin coaxial cables.

Task 2: Sensor measurement system development - - A portable PC-based data acquisition system was developed for the sensors developed in Task 1. This system delivers the high voltage electric pulses to the transmitting transducer and collects and processes the ultrasonic signals received by the receiving transducer through a Matec pulser/receiver board and a Sonix A/D board. The system is completely controlled by the host PC. The software that manages the hardware, processing and display of the sensor responses during cure monitoring was specially designed and developed using both C and HP-VEE software. A separate PC system for the vibrational response study was developed under this task. This PC system, which controls an HP function generator and a LeCroy digitizing oscilloscope, was configured to perform sweep frequency scans of the spectral response of the composite parts.

Task 3: Sensor experiments on flow/cure monitoring - - The capability of the WWG sensor developed in Task 1 using the measurement system developed in Task 2 was demonstrated. The effectiveness of the embedded sensor was demonstrated through RTM and SCRIMP experiments. In the RTM experiments, parts in a ½" x 8" x 8" mold were produced. In the SCRIMP experiments, both the ½" x 8" x 8" and a 18" x 36" molds were used. The large mold has 4 sections ranging from 0.5" to 2" thick in 0.5" steps. Experimental results showed when: a) resin flow reached the sensor, b) gel started and c) cure was sufficiently completed. This is especially evident in the large mold where sensors were placed in each of the different thickness sections.

Task 4: Dynamic vibrational response measurement - - It was also demonstrated that the sensor embedded in the composite parts manufactured in Task 3 can also be used to monitor vibrational responses of the parts. By introducing vibration through adhesively bonded or taped piezo-actuators, the structural vibration characteristics can be obtained. Furthermore, after subjecting these samples to specific impact damage, the difference in the vibrational responses in these samples was detected. Another damage detection method was investigated using the sensors embedded in the composite

parts as regular ultrasonic transmitter/receivers. Waveform distortions were detected as a result of the impact damage.

Task 5: Final report preparation - - Further processing of the data collected in Tasks 3 and 4 were performed. The results are included in this report which is submitted as the project deliverable. A separate video tape will also be prepared and a copy will be delivered to the Army technical officer in charge of this project.

The accomplishments listed above established the technical feasibility for the proposed WWG sensor technology. With this technology, intelligent, real-time control of the liquid molding composite armor manufacturing process can be achieved and the composite structures become "smart" armor structures.

II. PROJECT EXECUTION BY TASKS

TASK 1: SENSOR/TRANSDUCER DEVELOPMENT

The objective of this task was to develop a WWG sensor that is effective, easy to manufacture and implement. The task was divided into three related subtasks: 1) sensor element design, 2) transducer development, and 3) sensor evaluation in neat resin.

Sensor element design

Research was performed to design appropriate waveguide sensor elements. The parameters investigated were primarily waveguide shape and cross section geometry. Initially, an E-shaped waveguide made of stainless steel shim stock was considered. It was quickly discovered that the sharp edges of the shim sensor had undesirable influences on the received ultrasonic signal such as a change in the waveform shape. Another approach involving the use of flat ribbon wire was also examined and abandoned because of problems associated with consistent connection to the transducer elements. After some additional research and study, it was found that sensors made of stainless steel wires with a shape shown in Figure 1 gave the most consistent and satisfactory results in the neat resin experiments. The sensor shape is designed like the cross section of a light bulb so that the two parallel sections are close yet the curvature does not impede the passage of an ultrasonic wave of relatively long wavelength.

The first batch of "bulb" sensors were made of round stainless steel wire. It was successfully applied in neat resin experiments and later in Task 3 in the RTM process. Unfortunately, when it was applied in the SCRIMP experiments, it did not perform satisfactorily. As was discovered later in Task 3, the vacuum produced in the SCRIMP process caused excessive pressure on the sensor wire by the neighboring layers of fabric such that its sensitivity and sensing consistency were greatly reduced. To solve this problem, the sensor design was modified to have a square cross-section. The main idea was to reduce the area where fibers were in intimate contact with the sensor wire under the vacuum pressure and, at the same time, permit resin to reach the side surface of the sensor. As will be shown later, this modification played a critial role in the success of this project.

Transducer development

The research study was focused on developing compact, efficient and rugged transducers for the WWG sensor. The goal was to produce transducers that operate at about 300 kHz or higher. Initially, the main reason for this frequency target was to obtain time-of-flight information for the propagating waves. The first approach considered to achieve this frequency was an interdigital concept. However, an alternative was identified where selectively cut piezoelectric plates could be used. This method was proven to be very efficient and cost effective. Consequently, no research effort was devoted to the interdigital transducer concept.

The effect of transducer operational frequency on the sensor performance was investigated. Factors considered included: a) the size of the piezoelectric plates, b) ease of fabrication, c) the consistency in transducer/sensor integration, d) the length of WWG sensor in relation to the ultrasonic

wavelength, e) the fidelity of the propagated waves, f) the resolution needed for time-of-flight measurement, and g) the ruggedness of the final transducer/sensor assembly.

Based on the overall consideration, it was determined that 350 kHz was an appropriate operating frequency. After selecting the frequency, procedures were established for fabricating the transducers.

The sensor/transducer embedment implementation was achieved through using miniature coaxial cables. The coaxial cables carry the electric energy to the transmitter and relay the received signal from the receiver. This method proved to be an excellent choice. Under the original plan, the possibility of having the transducers external to the mold and leaving only the sensor embedded was also to be investigated. This approach was rejected from the beginning since it would need long acoustic waveguides to transmit acoustic energy to and from the sensor. This imposed a very stringent requirement for proper handling of the transducer/sensor assembly which rendered the technology impractical in a manufacturing environment.

Figure 2 is a photo of two complete transducer/sensor units. No special tuning is required of the transducers in the sensor. This sensor can be easily made to operate consistently at one frequency (350 kHz) with a sensitivity variation of no more than ±3 dB in the air.

<u>Sensor evaluation in neat resin</u>

Many experiments were conducted in neat resin with embedded WWG sensors. These experiments were designed to make preliminary suitability evaluation of the sensor developed in this task. They were conducted using a small reusable Teflon tray at room temperature. The main resin used was Shell Epon828+Epicure3234 which was selected for availability and representative characteristics. Figure 3 is a picture of such a setup with two WWG sensors.

Referring to Figure 1, there are two paths for the ultrasonic wave to propagate from the transmitting transducer to the receiving transducer. Path #1 is the route followed by the energy propagated through the wire itself. Path #2 is the route followed by energy propagated between the two parallel legs of the wire. These two paths provide the information that describes various stages of a cure process.

The typical amplitude responses from the neat resin experiment are shown in Figure 4. In addition to the temperature curve obtained from a thermocouple, there are two curves showing the amplitude responses from Paths #1 and #2. Path #1 shows when the resin reaches the sensor, the viscosity change and the gelation. Path #2 provides information on the resin hardening through the completion of the cure.

Before the resin was poured into the Teflon tray, ultrasonic energy propagated in the sensor wire. When the resin was poured in, some energy leaked out of the wire, causing a drop in the amplitude. As the curing process progressed, the resin viscosity decreased slightly. This is reflected by the small amount of increase in the transmitted energy in Figure 4. Before significant gel occurred in the resin, most of the received energy propagated through Path #1. The waveform shown in Figure 5a is a typical signal for Path #1 at this stage.

As the gel progressed, the amount of energy propagating through the wire decreased rapidly. Meanwhile, the resin began to harden and provided sufficient support for the ultrasonic energy to propagate via Path #2. Towards the end of cure, the resin reached its viscoelastic asymptote as indicated by the flattening of the amplitude response for Path #2. Since Path #2 is a shorter distance, its signal arrives earlier than that of Path #1. This is evident in Figure 5b. In fact, because of the choice of frequency, signals from the two paths were time-gated to provide separate amplitude responses for the two paths.

Time-of-flight information was also obtained for the experiment in Figure 3. The results are presented in Figure 6. The response for Path #2 shows an increase in velocity as the resin hardened. Note that the time-of-flight for Path #1 reached a maximum before the gelation was complete. This seems to be typical in all the neat resin experiments conducted in this project. In Phase I of this program, it was decided to focus on the amplitude response due to the simplicity in interpretation. Only limited effort was allocated to the time-of-flight responses. We do plan to take a closer look at the time-of-flight information in Phase II.

Accomplishment

In this task, a low-profile, effective WWG sensor that is capable of monitoring the flow/cure of resin was developed. The sensor has a small footprint and is constructed with two piezoelectric plates bonded to a specially shaped stainless steel wire. The sensor operates at 350 kHz with high efficiency and consistency. It is easy to make and simple to install. Through evaluation in neat resin, the sensor functionality was demonstrated. As will be discussed and shown in Task 3, the developed WWG sensor also worked well in liquid molded composites.

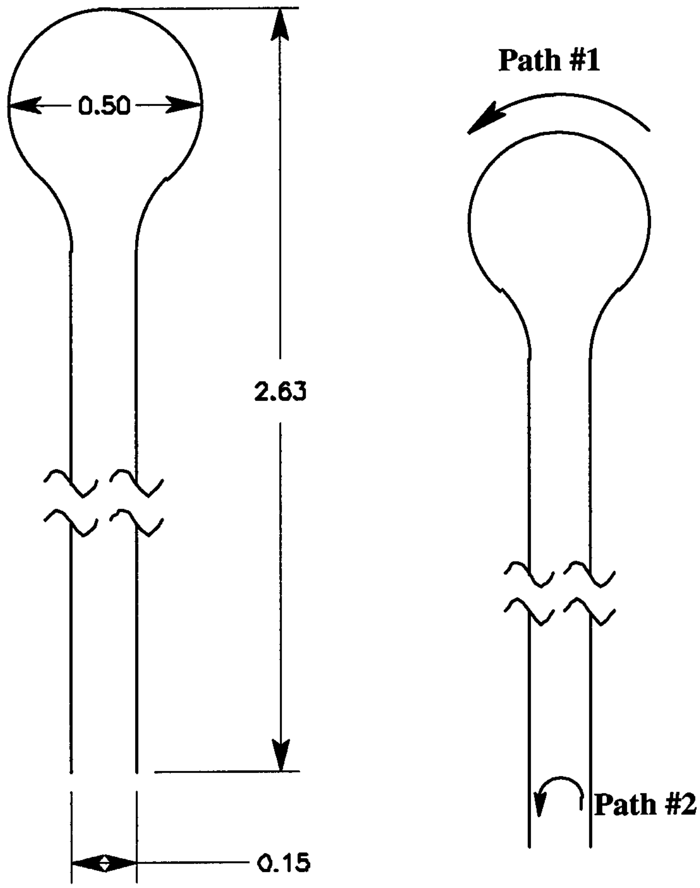


Figure 1. WWG sensor shape and wave propagation paths

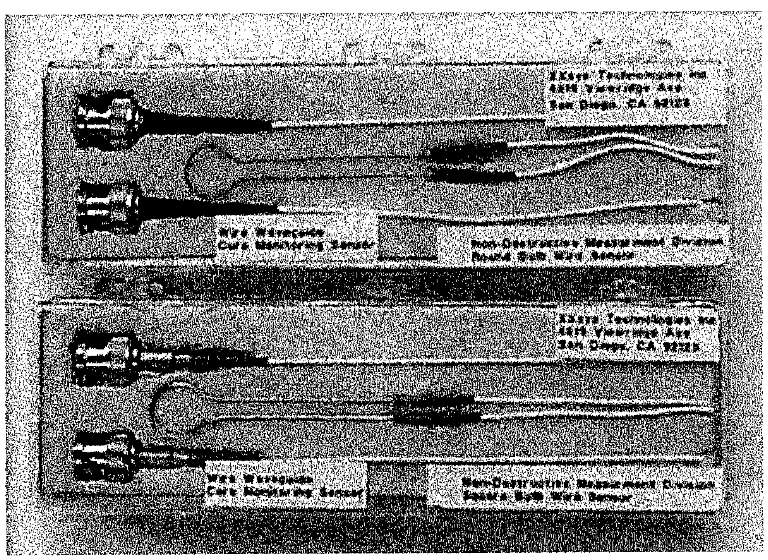


Figure 2. Photo of two WWG sensors

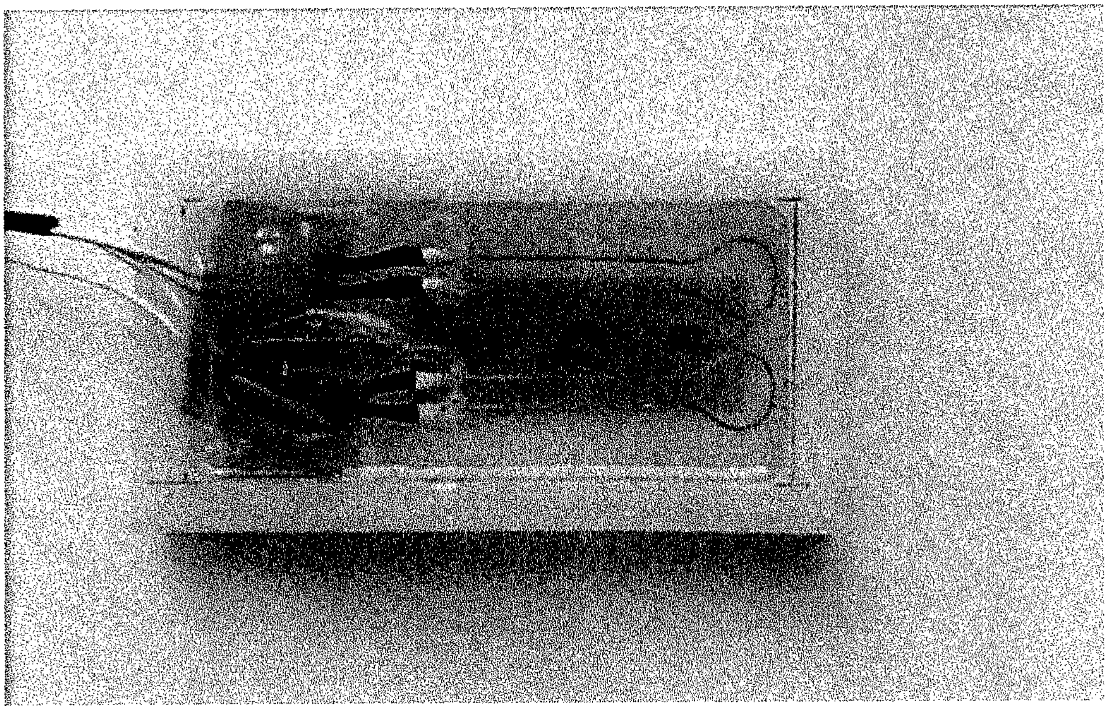


Figure 3. Neat resin experiment

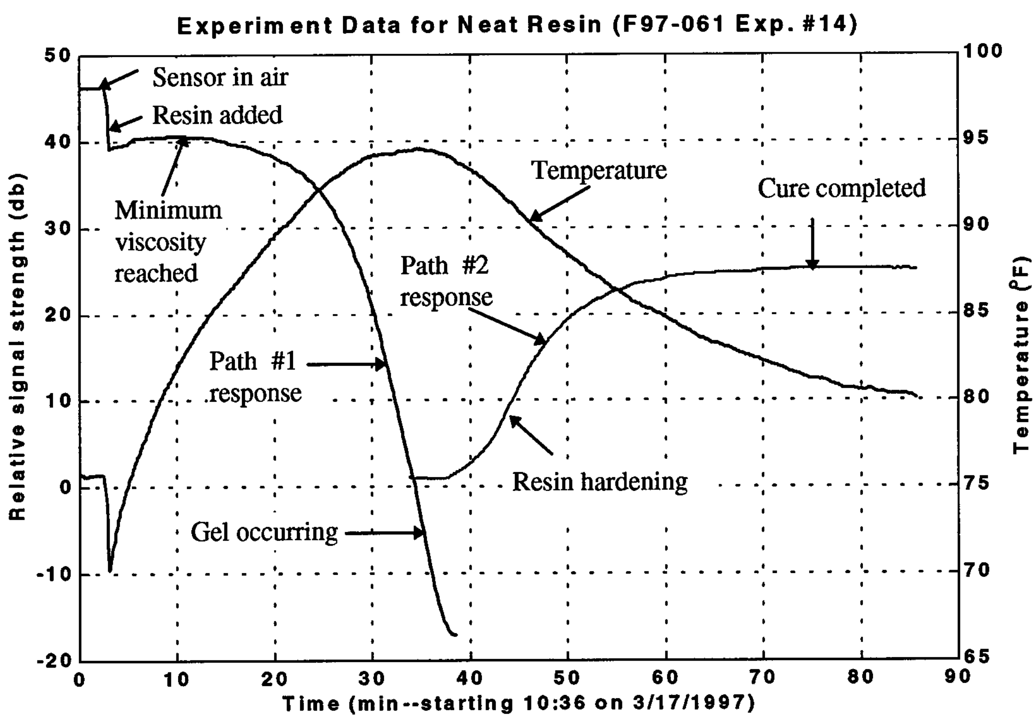
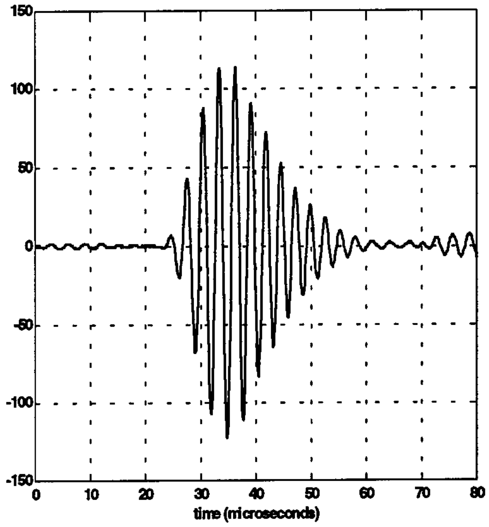
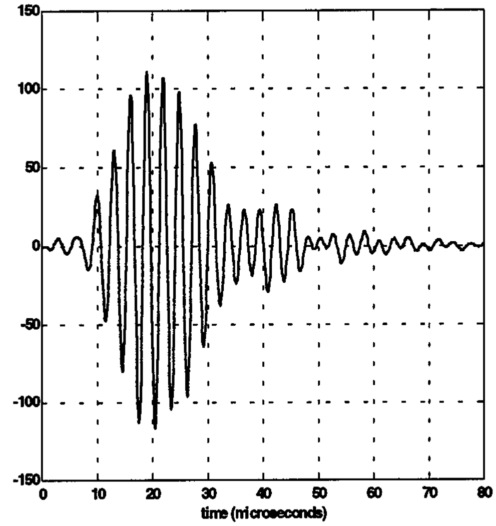


Figure 4. Typical amplitude responses of a WWG sensor



(a) Path #1



(b) Path #2

Figure 5. Typical waveforms for Paths #1 and #2

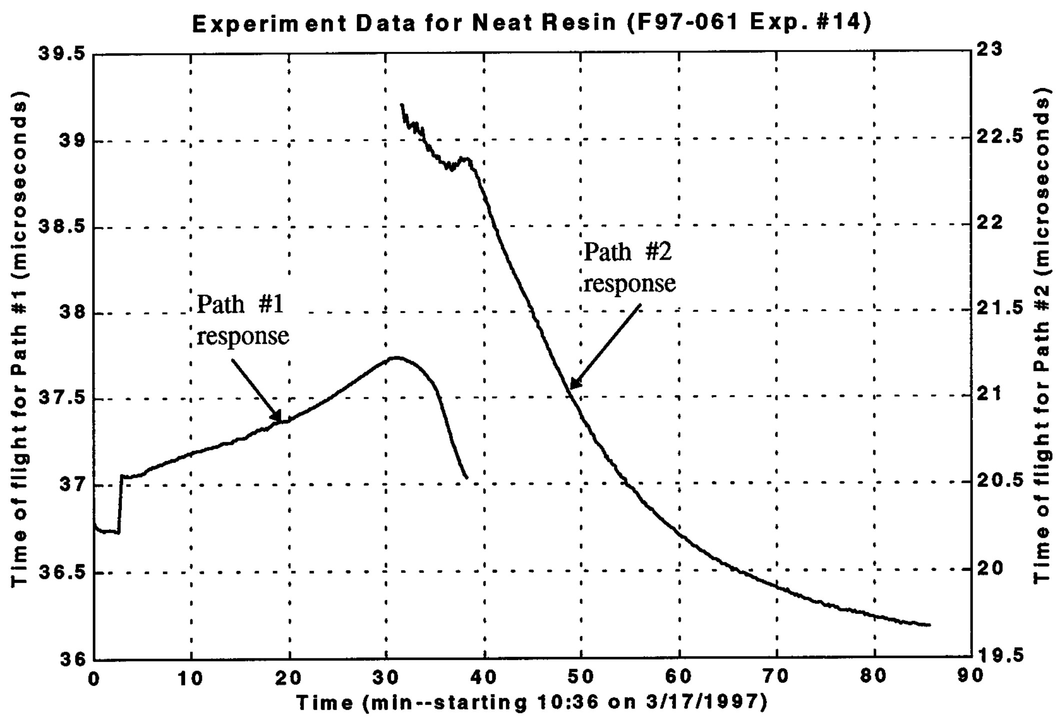


Figure 6. Typical time-of-flight responses for Figure 4

TASK 2: SENSOR MEASUREMENT SYSTEM DEVELOPMENT

The purpose of this task was to develop appropriate data acquisition systems for the experiments in Tasks 1, 3, and 4. Three separate systems were configured for the WWG sensors: two for the cure monitoring (Tasks 1 and 3) and the other for the vibration study (Task 4). All systems were PC-controlled automated measurement systems. The software that controls the system hardware and processes collected data were all developed in-house using C and HP-VEE programming languages. In these systems, C was used to perform fast system control and data processing where HP-VEE was used to provide user interface. This proved to be a good combination as many experiments in this project required change of display for different types of output and data visualization.

System I

System I was configured to make a single sensor measurement in each experiment. It was primarily used in Task 1 for sensor development. It consisted of three PC boards and three separate instruments. The PC boards were Matec TB-1000 pulser/receiver card, Sonix 825 A/D card, and Omega T5508 thermocouple card. Due to the limitation and pulse jitter problem in the pulser section of the Matec board, only the receiver section was used. The laboratory instruments were HP3312A arbitrary waveform generator, ENI 2100L RF power amplifier, and optional Lecroy 9310 digitizing oscilloscope. The diagram for this system is shown in Figure 7. Under the PC control, the received ultrasonic signals were always automatically amplified to the full scale of the A/D range. Typically, signals were averaged 16 times before being stored to the PC hard disk.

System II

This system was designed for multi-sensor operation. It is also a self-contained portable Dolch-PC system. This system was put together after completing Task 1 and the sensor design and operation parameters were frozen. This system was used extensively in Task 3 for the composite experiments. It consists of a new Matec TB-1000 card, a Sonix 825 A/D card, a ComputerBoard digital I/O card, and an Omega T5508 thermocouple card. Externally attached to the PC are two-8 channel multiplexers controlled via the digial I/O card. The diagram for this system is shown in Figure 8 and a photo of the computer system is given in Figure 9.

The software for this system is similar in function to that of System I but is much more comprehensive because it has more information to process and display during run time. Several rounds of modifications and updates were done to the system software to handle the change of experimental procedure variation. Figure 10 is the software user-interface screen. This system can be carried to a potential manufacturing site for demonstration.

System III

This system is a reconfiguration of System I after System II became operational. It is designed and used for vibration study only. The PC controls the HP33120A, collects datafrom Lecroy 9310 and displays the results via software written in HP-VEE. Figure 11 is the system diagram and Figure 12 is a photo of the system. Note that the sensor is connected to the digitizing oscilloscope; no separate amplifier was used in this system.

There were also efforts to develop time-of-flight algorithms for real-time calculation. This called for automation involving extensive C programming to account for various circumstances. Many times the software failed in the middle of an experiment causing the entire experiment to be aborted. As a result, this effort was devoted to post rather than real-time processing. In Phase II, this subject will be revisited.

Accomplishment

A portable multi-sensor PC-based data acqusition system for flow/cure monitoring and a separate laboratory system for vibration study were developed. Software that controls the hardware and processes the sensor signals was also developed. These systems played vital roles in the experiments performed in Tasks 1, 3, and 4.

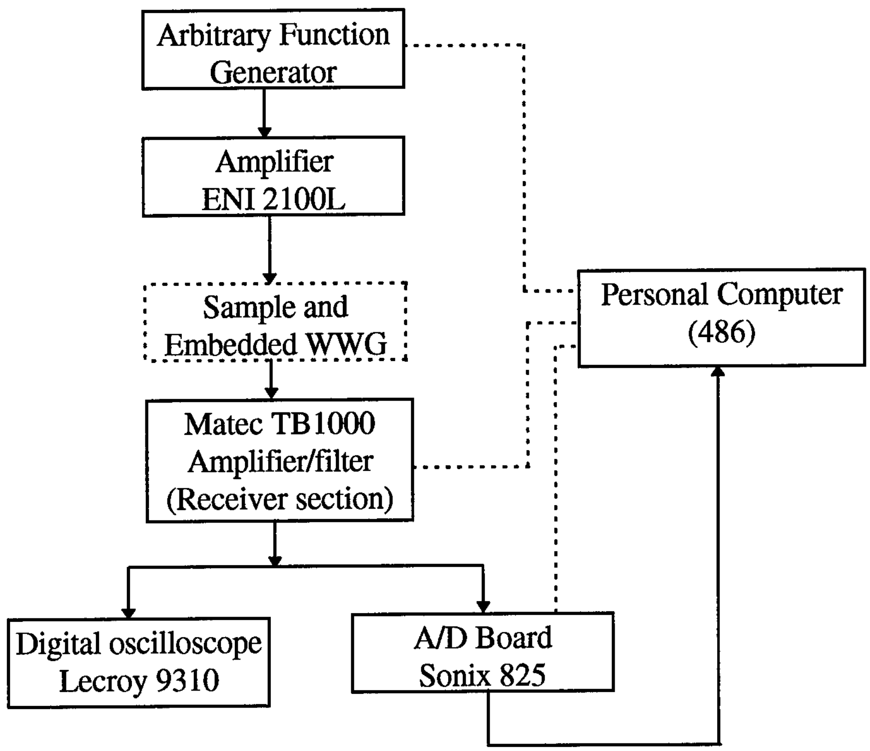


Figure 7. Schematic diagram for system I

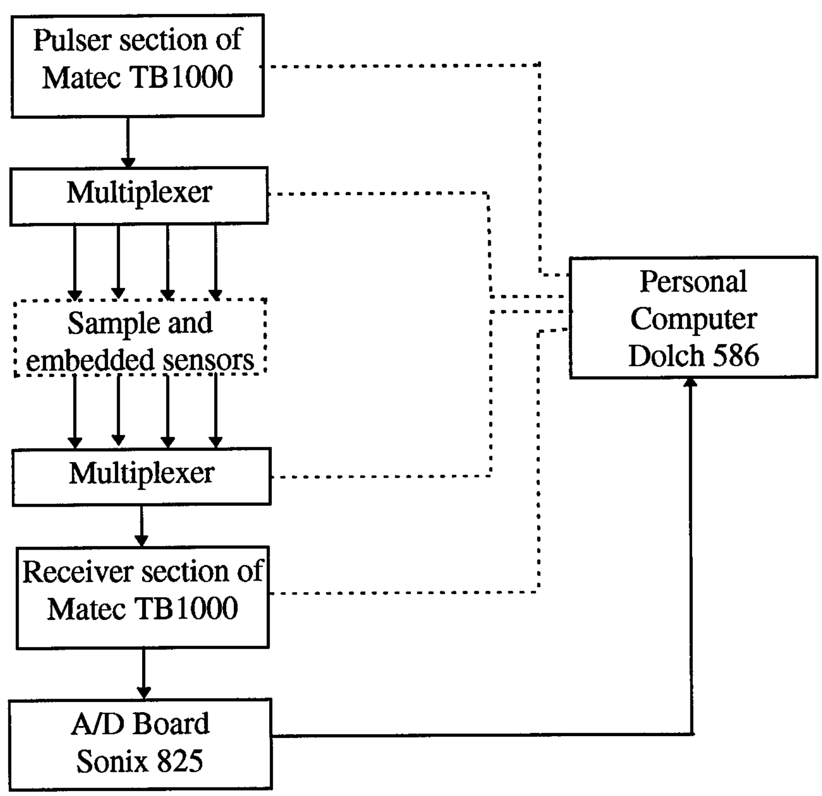


Figure 8. Schematic diagram for system II

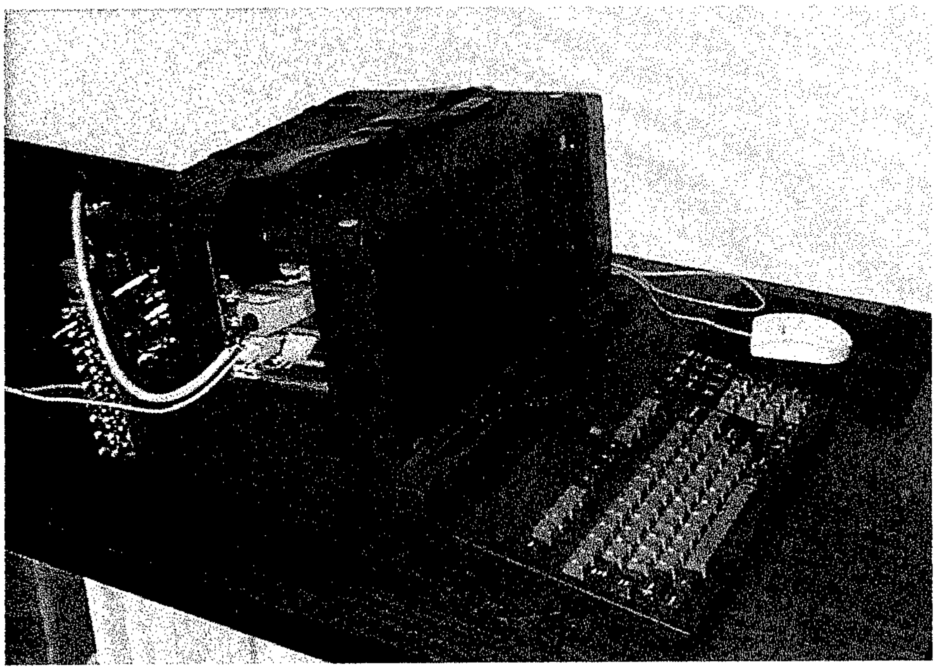


Figure 9. Photo of the portable Dolch data acquisition system

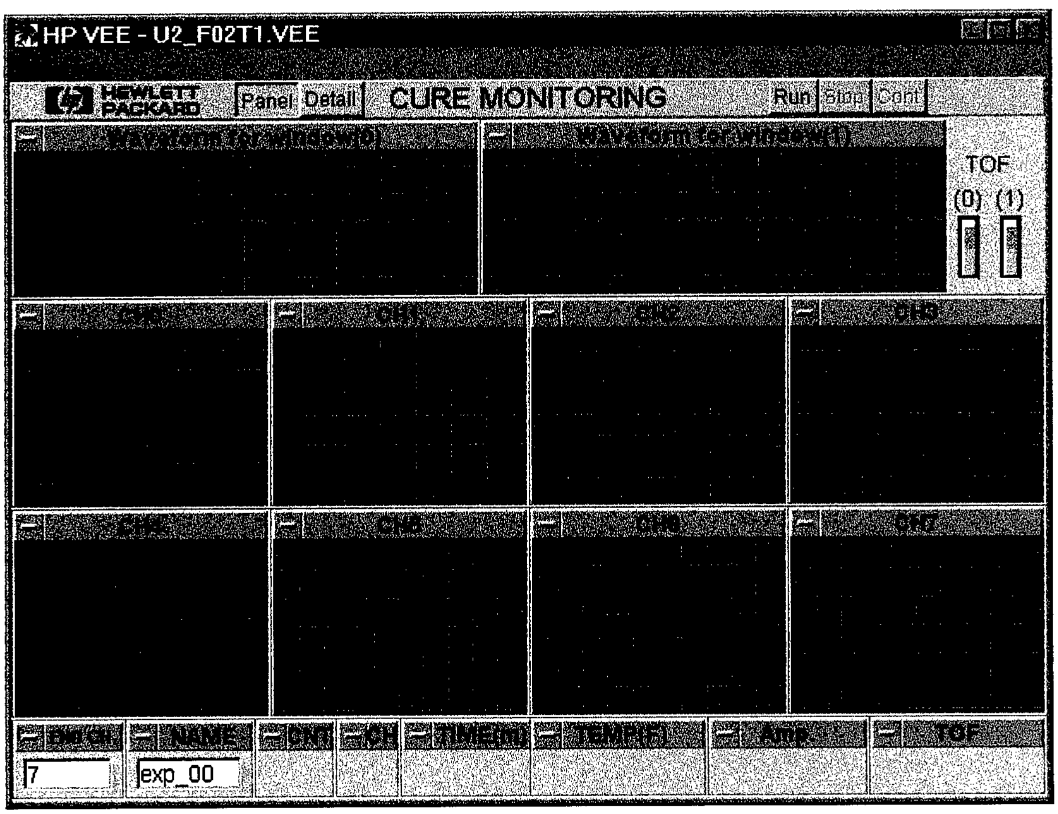


Figure 10. User interface screen for System II

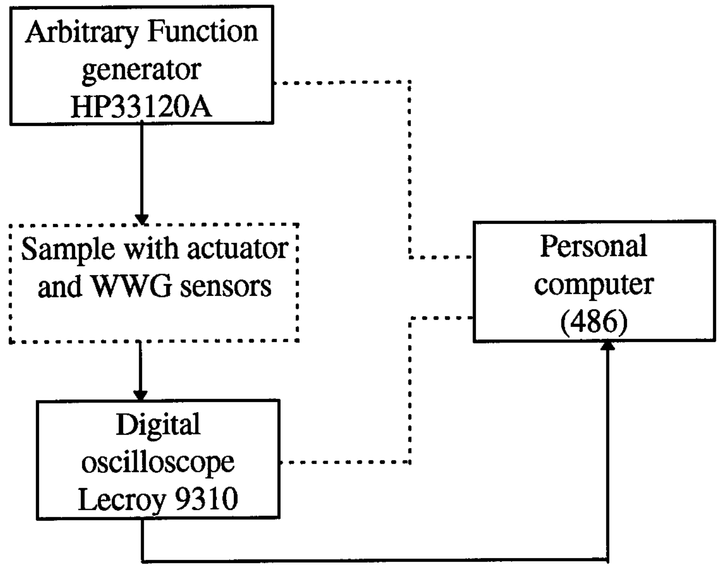


Figure 11. Schematic diagram for system III

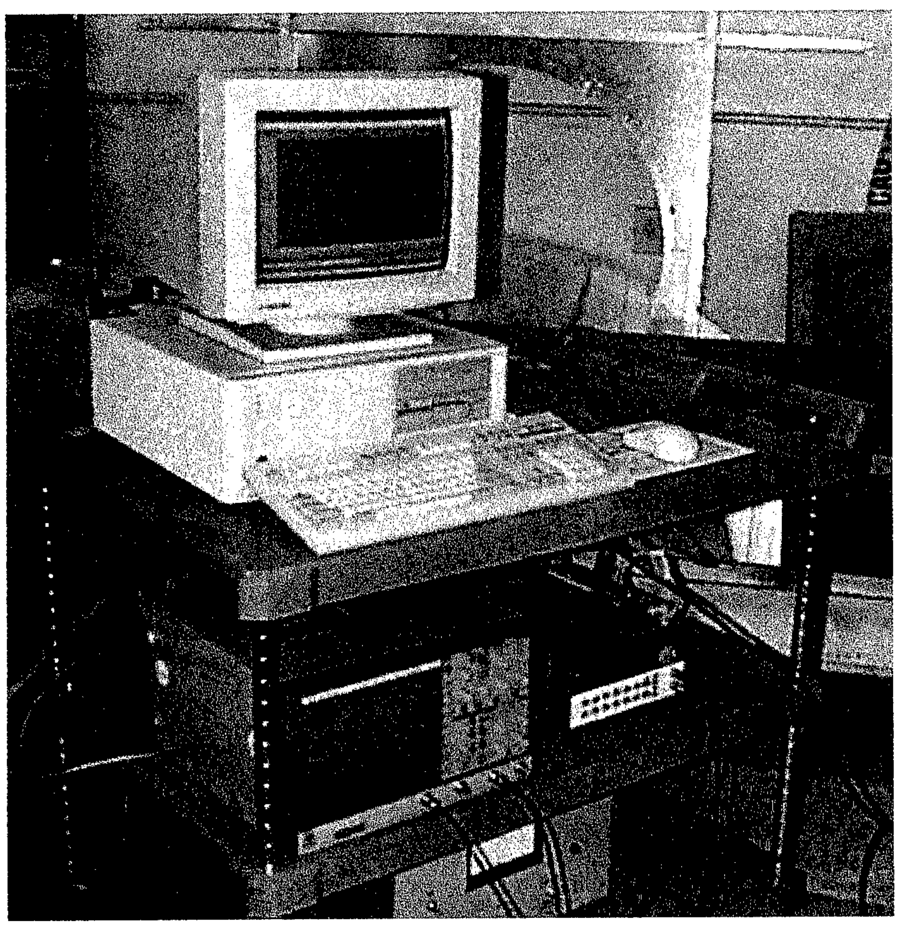


Figure 12. Photo of vibration measurement system

TASK 3: SENSOR EXPERIMENTS ON FLOW/CURE MONITORING WITH RTM/SCRIMP PROCESS

This task was designed to demonstrate the effectiveness of the sensors developed in Task 1 in the liquid molding composite manufacturing processes. Experiments were carried out in three components: 1) an RTM mold of ½" thick 8" x 8" composite part, 2) a SCRIMP mold of ½" thick 8" x 8" composite part, and 3) a SCRIMP mold of an 18" x 36" large part with four different thickness sections. The mold for 2) was the same as that for 1) except that only the lower half was actually used. Both the small and the large molds were made of aluminum. All the experiments were carried out at the RTM Division of XXsys using 40 oz /yd sq. heavy tooling glass cloth manufactured by Hexcel. System II developed in Task 2 was used throughout this task.

Demonstration experiments with RTM

Several experiments were carried out with the RTM process. Typically, 7 plies of fabric and 4 sensors were used in each experiment. After the layers of fabric were placed in the mold and sensors embedded in the middle layer, the mold was tighten by eight C clamps. Resin was then injected into the closed mold with thermocouple and sensor leads coming out from the side. The resin was injected from the bottom of the mold with vent ports on four sides as well as at the top. The resin used was Jeffco 1314A and Jeffco 3109B (4:1 ratio) which has a pot life of 15 minutes at the room temperature. Jeffco resin was selected because it was Shell 828-based and readily available.

Typically the injection was done with a cold or lukewarm mold. After the resin was injected, heat was applied to warm up the mold and speed up the cure process. Figure 13 is a photo of the mold and Figures 14 and 15 are typical amplitude and time-of-flight responses from the RTM process. The responses are similar to those shown in Figures 4 and 6 for neat resin. The major differences occurred shortly after the resin reached the sensor with a rapid increase in the amplitude for Path #1. It is speculated that this is due to the resin lifting the fabrics from the sensor wire. The rise, however, quickly stablized at a level lower than before the resin reached the sensor. An explanation for why the time-of-flight reduced (velocity increased) when resin just reached the sensor has not been sufficiently developed. In spite of this, it is clear that the sensor was able to detect when the resin arrived.

One may also note the differences in the scales of amplitude and time-of-flight between the data from RTM and those from neat resin experiments. The seemingly large differences in value are primarily due to the different normalization factors and trigger points between System I and System II. This should not be of a concern because the project focuses on the relative changes.

Demonstration experiments with SCRIMP in the small mold

The mold used for the RTM experiments was modified for SCRIMP experiments. Only the lower half of the mold was used. The entry point for the resin was moved to the side for convenience. The vacuum was achieved with bagging materials and a vacuum fitting on the

surface of the mold. In addition, a controlled heater blanket was placed under the base of the mold. Figure 16 is a photo of the system during an experiment. The resin used for SCRIMP was NanYa 128 ("828" based resin) with EAC100NC (Anhydrite) plus EAC catalyst (accelerator/promoter). The mixing ratio was 100:85:3. This resin system has a long pot life and low viscosity at 300 cps. This epoxy system was used mainly because of the availability and close relation between the supplier and XXsys. Another Shell system was also considered but was temporarily out of stock.

Figures 17 and 18 are typical responses obtained from SCRIMP process. Compared to those in the RTM, the responses were very similar except for minor additions of features due to the vacuum process as annotated on the figures.

It should be pointed out that the WWG sensor used in this experiment had a square cross section. In fact, this was the key to the project's success. When the SCRIMP experiments were begun the round-wire sensor was used. The round sensor was found to work quite successfully in the neat resin and in the RTM experiments as shown in Figures 4, 6, 14, and 15. However, there were serious problems with applying to the SCRIMP experiments. When it was realized why the round wire sensor did not produce desired result Task 1 was revisited to develop the square wire sensor. The need for change in sensor design can be explained as follows:

In the RTM process, the tightness of the glass cloth to the sensor wire was governed by how much pressure was applied with the C clamps. To prevent leakage from the sides of the mold, only a limited number of layers (7 plies) was packed. It was noticed that parts from RTM appeared to have low fiber volume fraction (about 29%). When making SCRIMP parts, normally 12 plies (about 50% fiber volumn fraction) could be packed. This was due to the larger pressure produced by the vacuum. This larger pressure caused the fiber to have very intimate contact with the sensor wire. It was estimated that about 75% of the sensor wire surface area was in contact with the glass fabric. As a result, a very large amount of energy leaked into the fiber before it completed the propagation in the wire. Meanwhile, the surface area used for "sensing" decreased significantly. Consequently, the sensitivity was greatly compromised.

To improve the sensitivity, the wire cross-section was changed from round to square. By using a square wire the fiber/sensor contact area was limited to 50%. The result was dramatic with very consistent and reproducible experimental results. A comparison of the two types of sensors in a SCRIMP experiment is given in Figures 19 and 20 for the amplitude responses. It can be readily seen that the vacuum caused the round wire to experience a 30 dB drop in amplitude but only a 10 dB drop for the square wire. It should be pointed out that the round wire result in Figure 19 was atypical. In fact, this was the only "successful" run for the round wire sensor. Interestingly but logically, both round and square wire sensors gave a similar response during resin hardening.

Demonstration experiments with SCRIMP in the large mold

After the new square wire sensor was developed and validated in the small mold SCRIMP, we proceeded to a demonstration in the large mold. The four sections of the mold are 0.5", 1.0", 1.5" and 2.0" in thickness. The resin used for this was the same as that for the small mold SCRIMP experiment. There were two resin entry ports located on one side of the large mold. A silicone heater blanket was placed under the base of the mold. To speed up the resin infusion process, special resin distribution tubes were used on the edge of the mold. Sensors and thermocouples were installed in the mid-layer of each of the four sections. The mold was not preheated but the heater was turned on about the time the resin was infused. Figures 21 through 23 are photos showing the mold, experiment setup and resin infusion process.

Again, the square wire sensors worked very well. Figures 24 through 27 are four sensor responses at four different thickness levels. The responses all have similar characteristics and resemble those in Figure 17 except that it appears the viscosity of the resin did not drop before gel occured. This may be due to a number of factors such as heating of the mold before resin was fully infused or the vacuum pump did not have enough capacity to produce quick second consolidation in the part. In spite of this, it can be clearly seen when resin reached the sensors, when gel occurred and when the cure was effectively complete.

Figure 28 is a photo of the finished part from this SCRIMP experiment.

Accomplishment

It was demonstrated through numerous RTM and SCRIMP experiments that the WWG sensors developed in this project can provide the resin flow and cure information very effectively. Particularly important was that the square WWG sensor worked very well in the presence of high pressure produced by the vacuum. The success in these liquid molding experiments provided definitive proof of the technical feasibility that the developed WWG sensors can be used to monitor the flow/cure of composites.

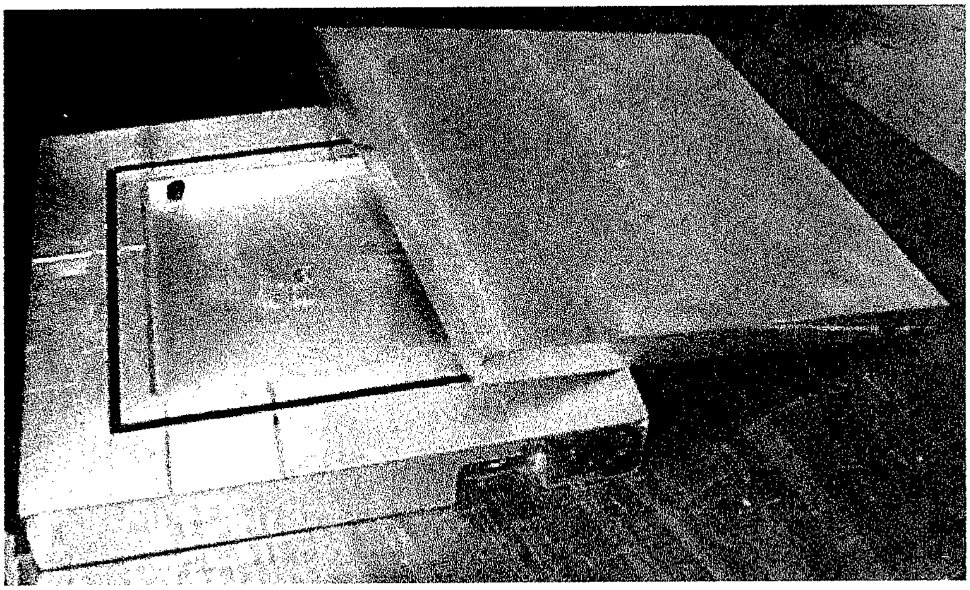


Figure 13. Photo of the RTM mold

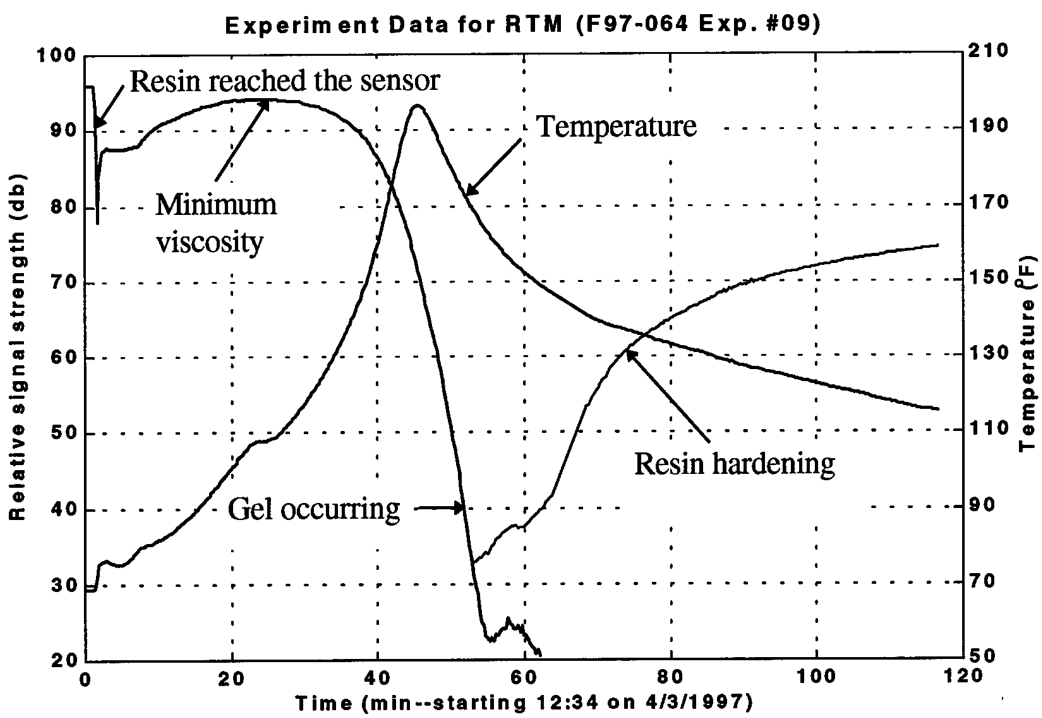


Figure 14. Typical amplitude responses for RTM experiments

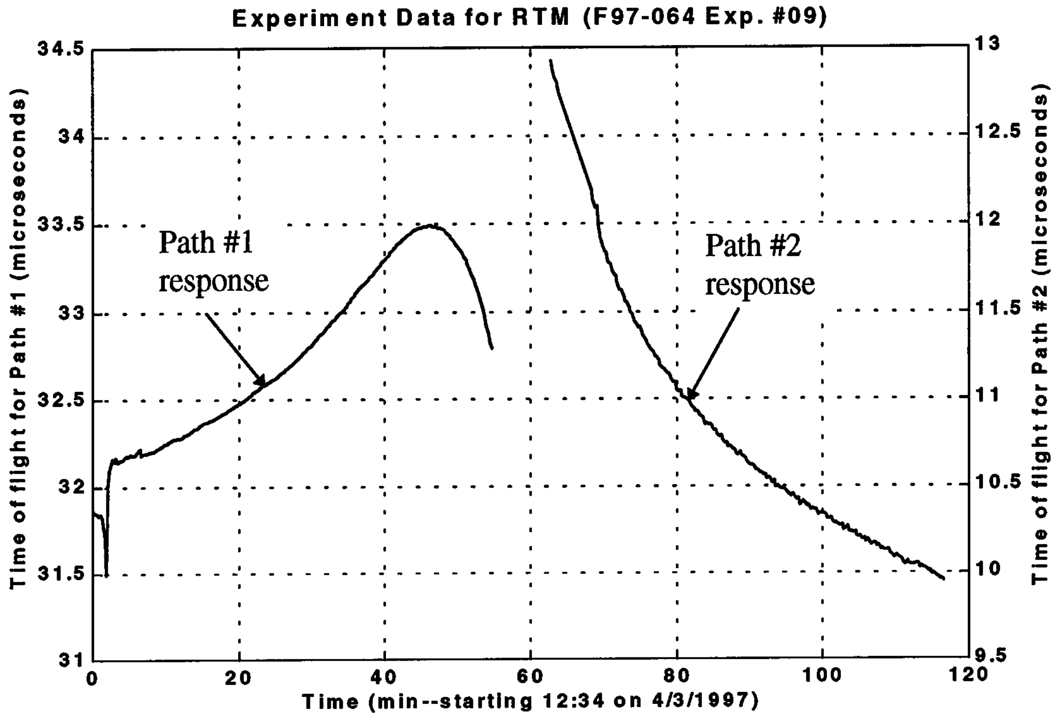


Figure 15. Typical time-of-flight responses for RTM experiments

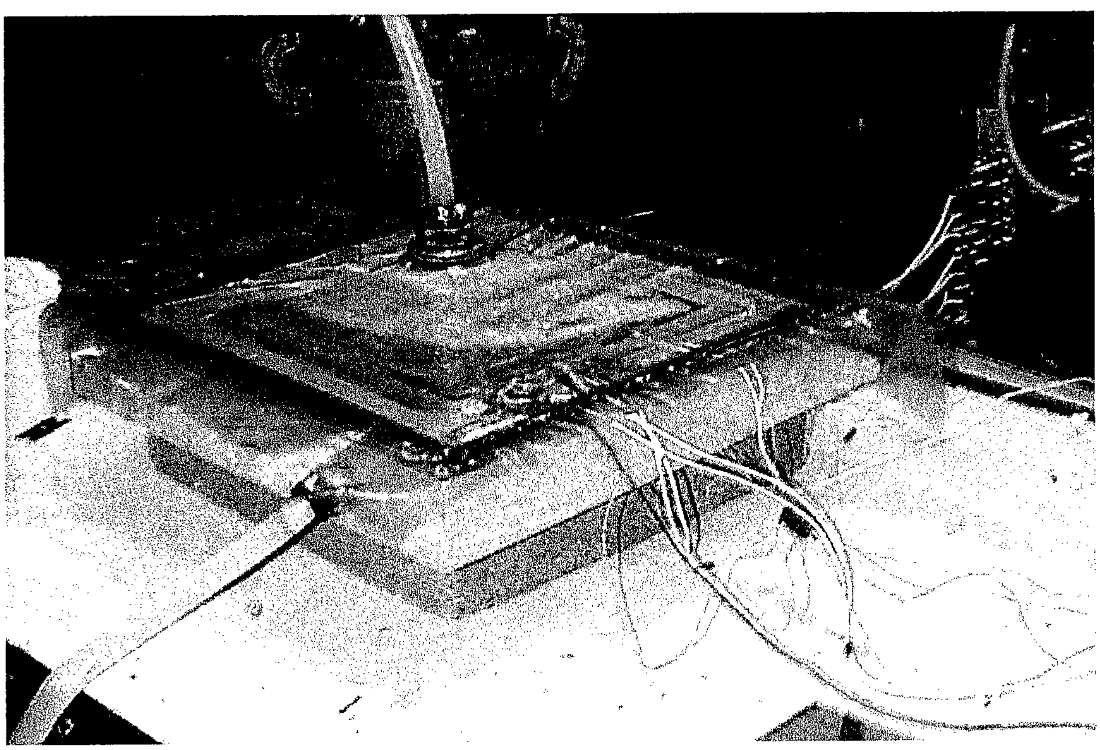


Figure 16. Photo of a small mold SCRIMP experiment

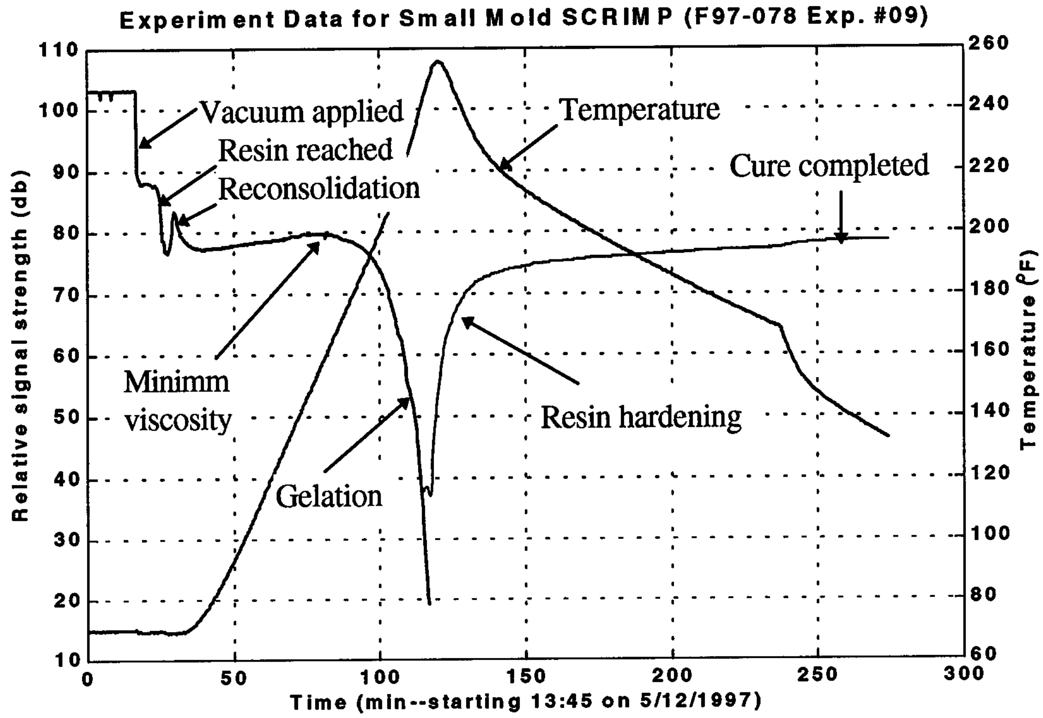


Figure 17. Typical amplitude responses for SCRIMP experiments

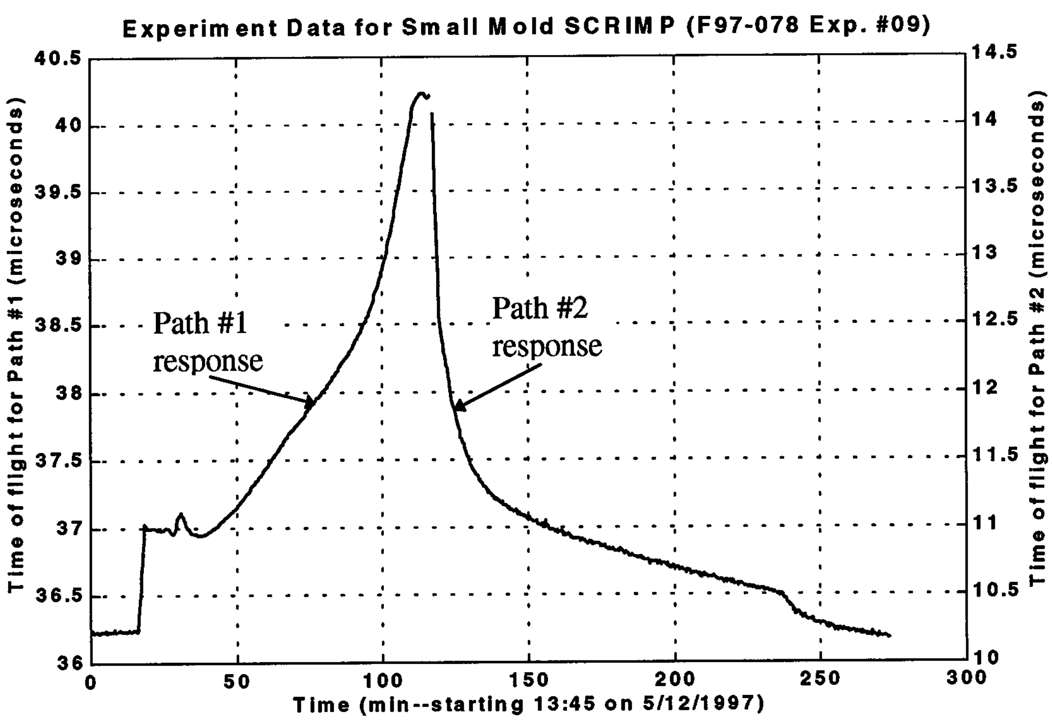


Figure 18. Typical time-of-flight responses for RTM experiment

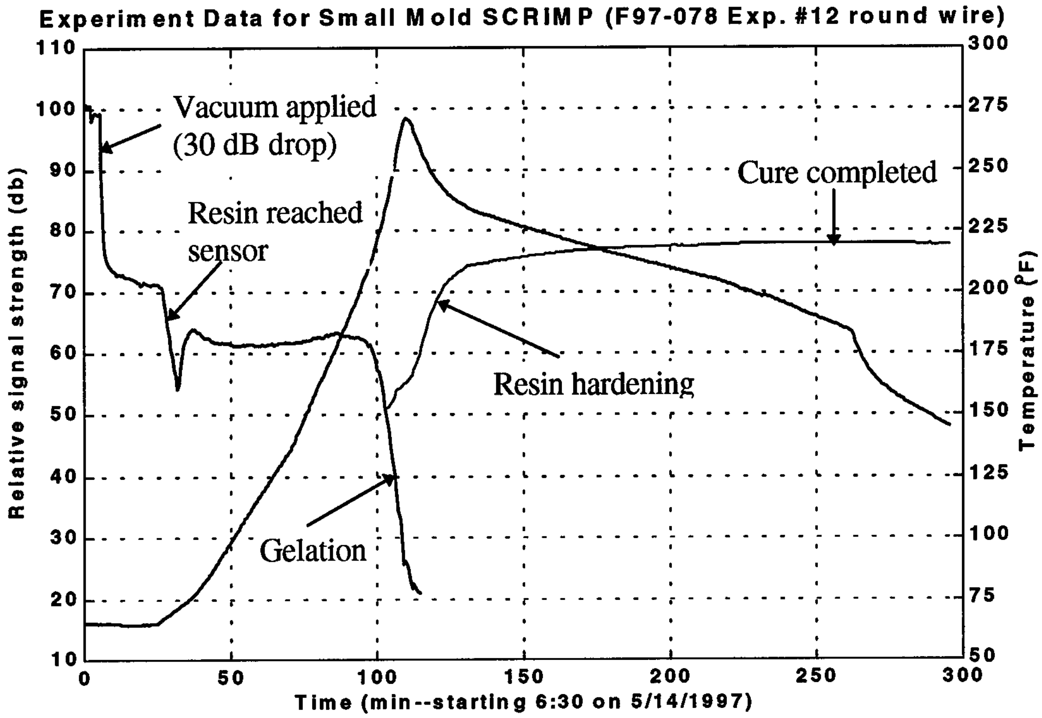


Figure 19. Amplitude responses for a round wire sensor in SCRIMP

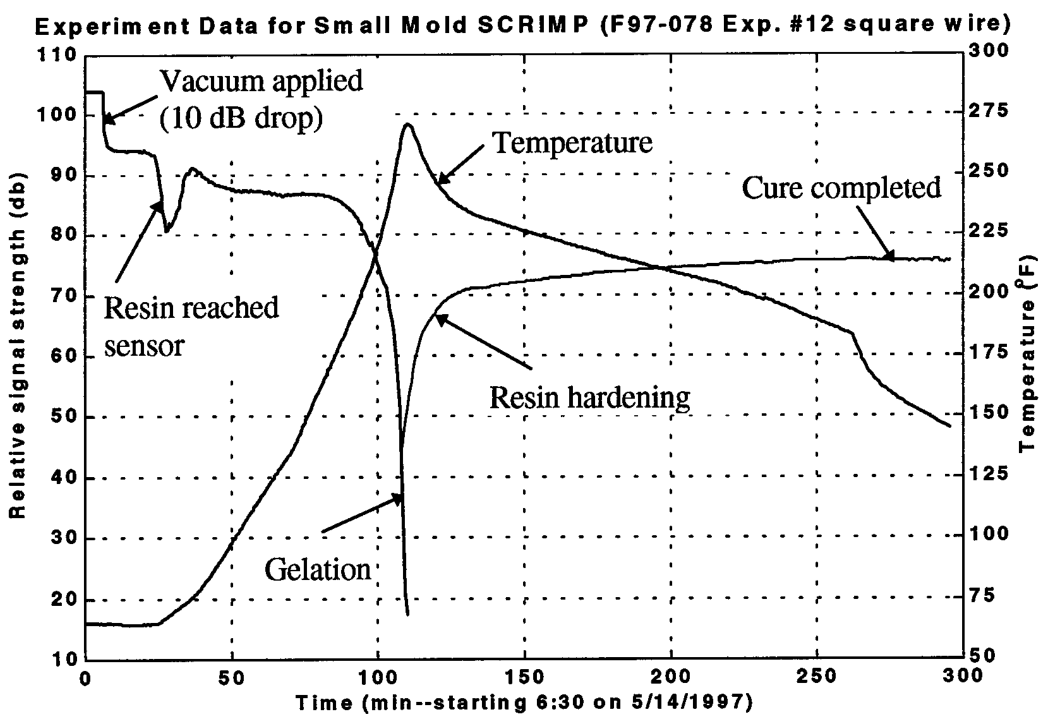


Figure 20. Typical amplitude responses for a square wire sensor in SCRIMP

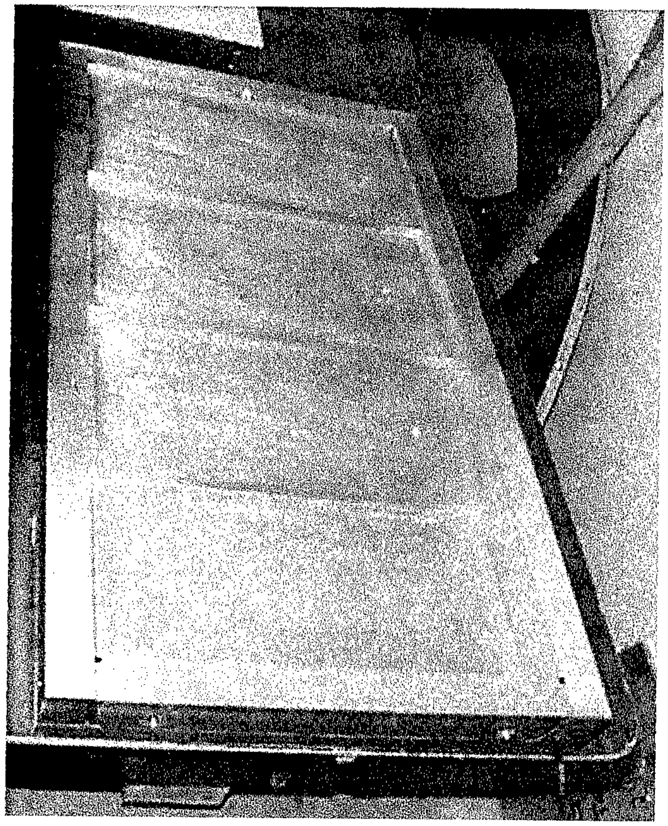


Figure 21. Photo of large mold for SCRIMP experiments

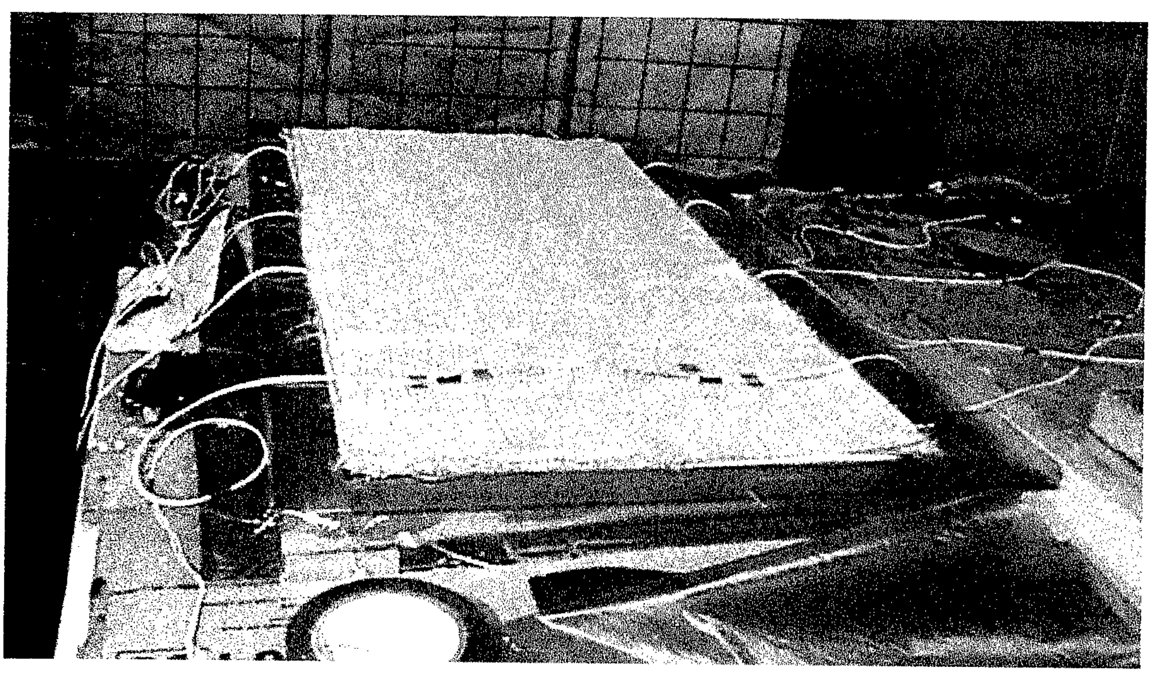


Figure 22. Sensor placement in large SCRIMP mold

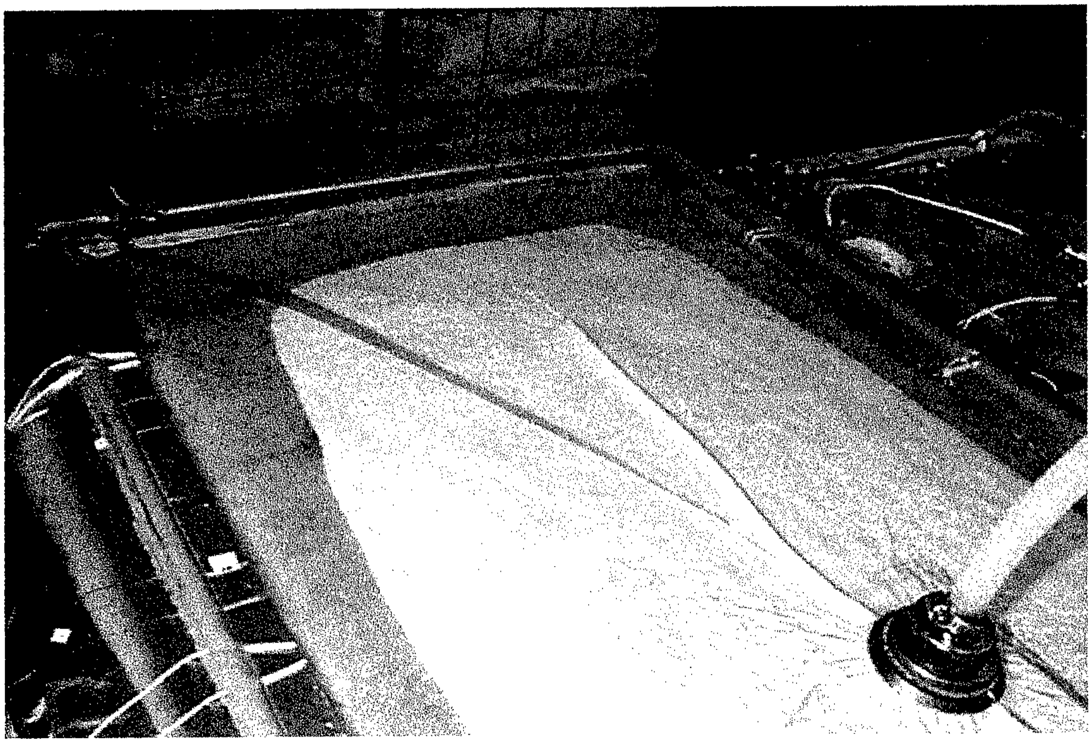


Figure 23. SCRIMP experiment in progress

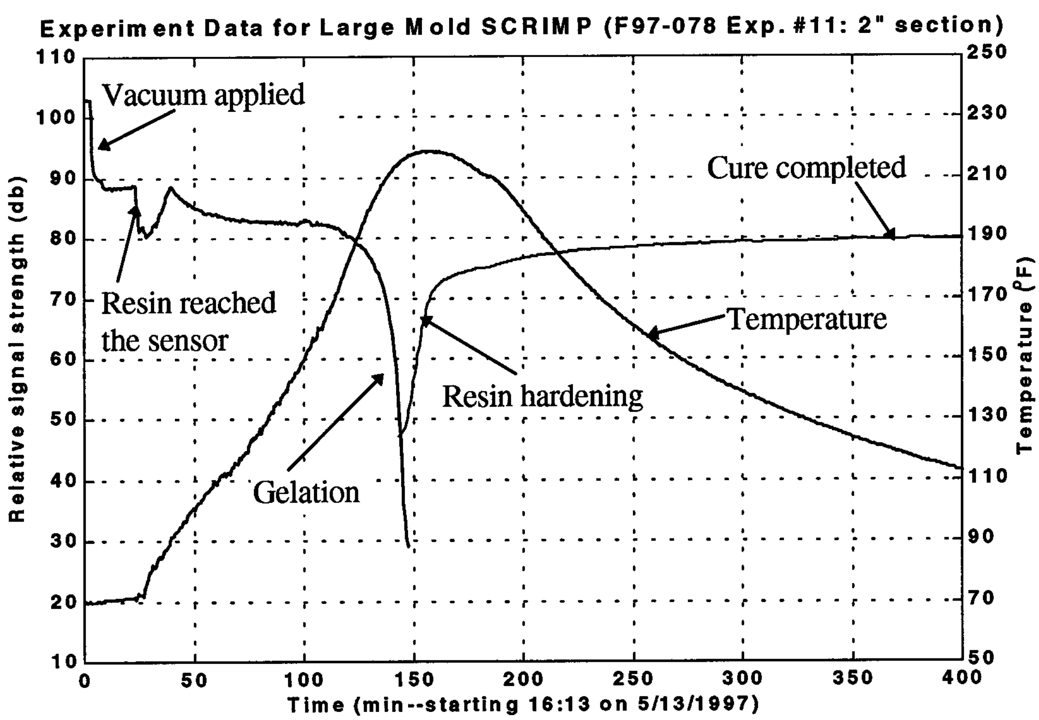


Figure 24. Amplitude responses of a WWG sensor at 2" section

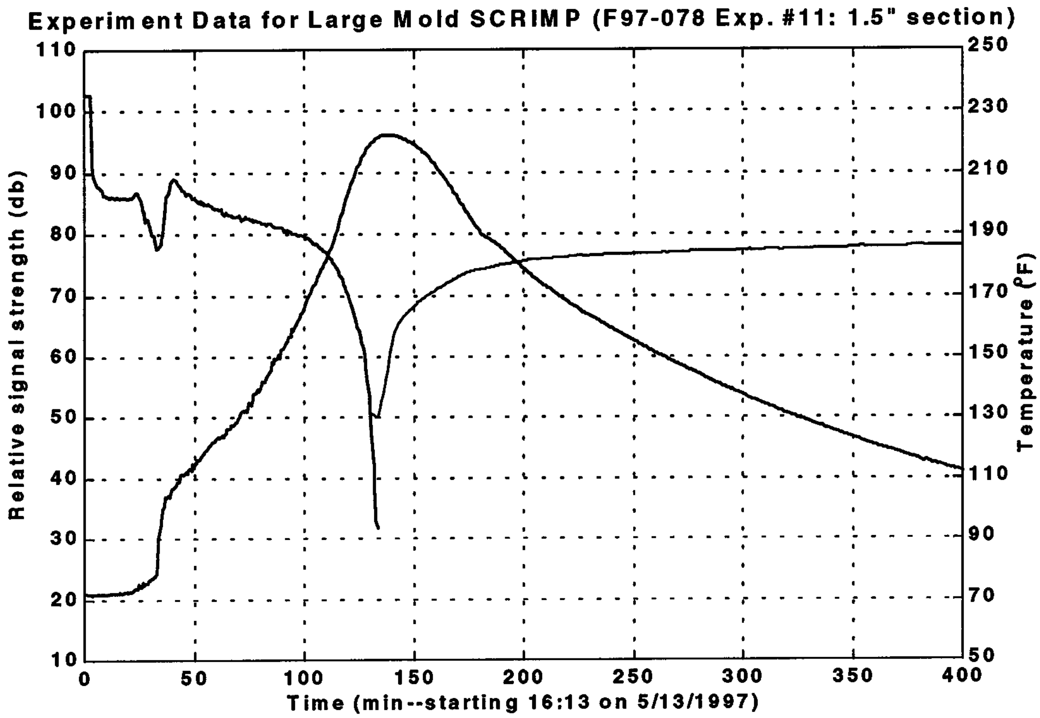


Figure 25. Amplitude responses of a WWG sensor at 1.5" section

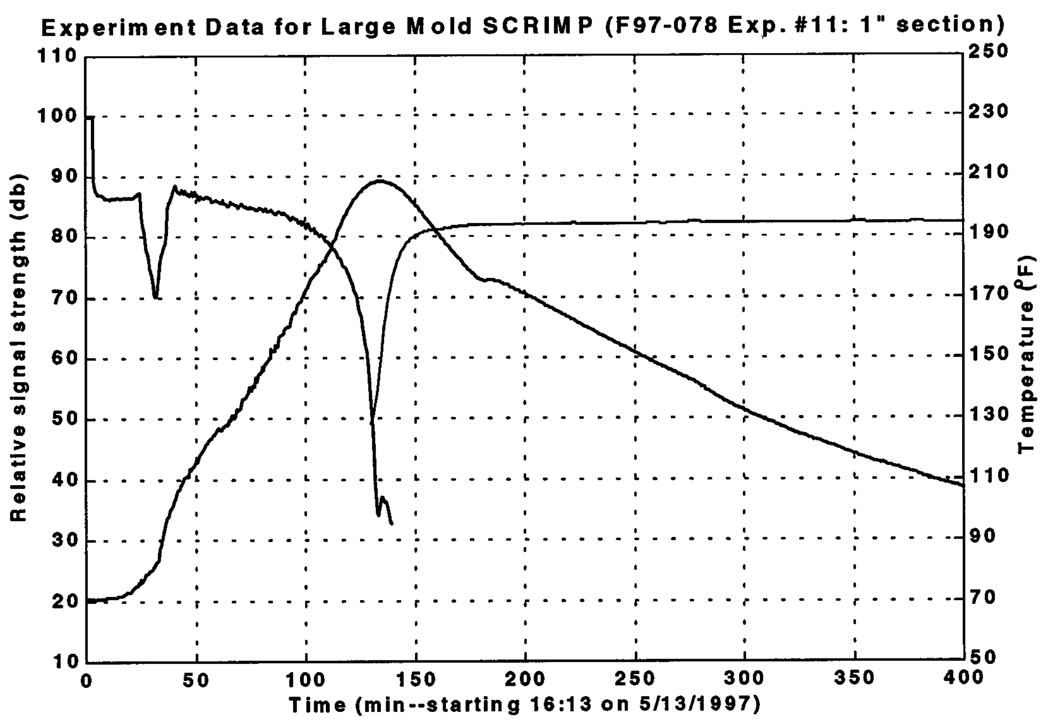


Figure 26. Amplitude responses of a WWG sensor at 1" section

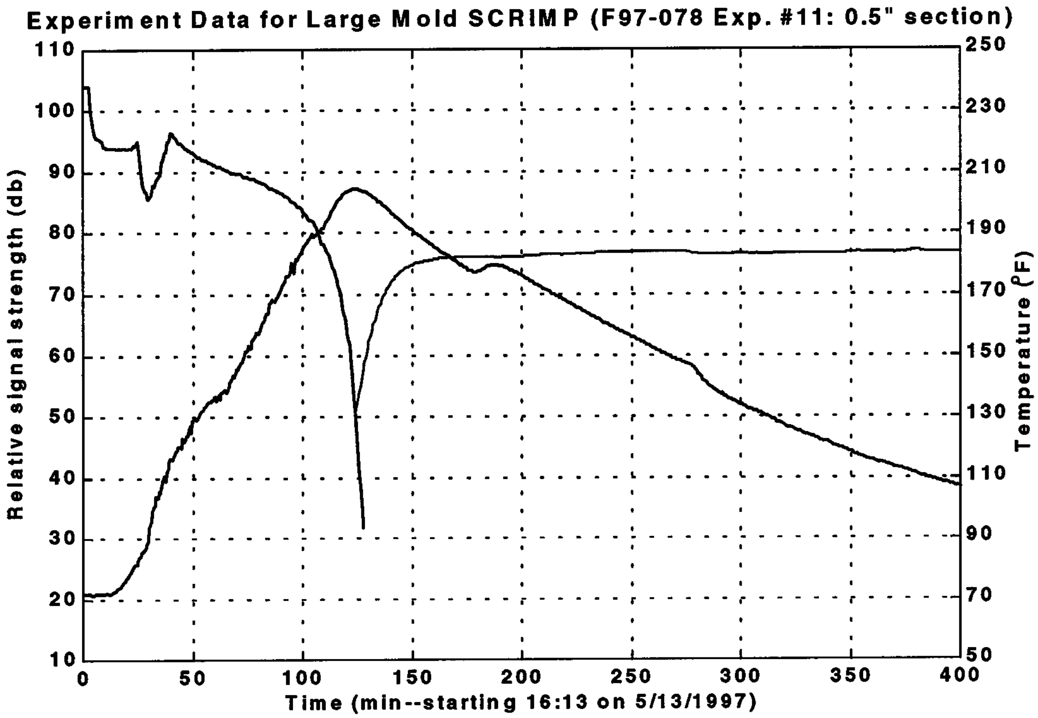


Figure 27. Amplitude responses of a WWG sensor at 0.5” section

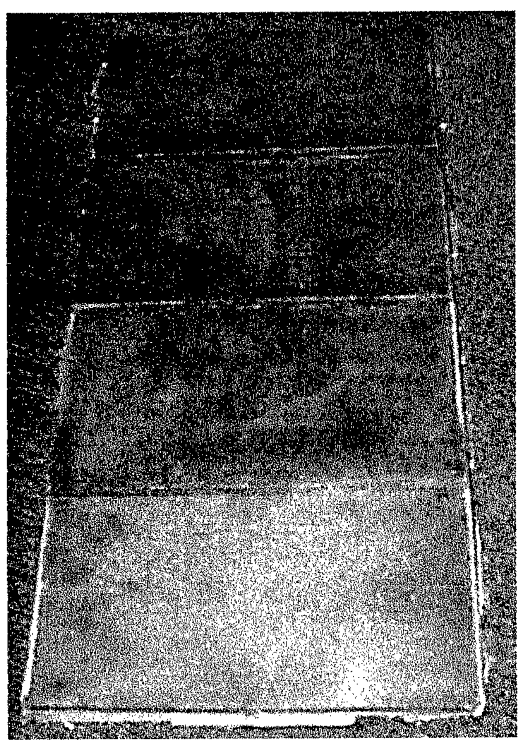


Figure 28. Photo of the finished composite part from a large mold SCRIMP experiment

TASK 4: DYNAMIC VIBRATIONAL RESPONSE MEASUREMENT EXPERIMENT

This task is to show that the WWG sensor for the resin flow/cure monitoring can also be used for the measurement of a structure's vibrational response. Composite parts fabricated from the small mold SCRIMP experiments in Task 3 with embedded WWG sensors were used for this task. Four parts were studied for impact damage detection. Piezo-actuators from Active Control Experts, Inc. were identified as the appropriate source for this study. These efficient actuators are low profile (~0.01" thick). Two different sizes were used during this task: 0.5" x 2" and 0.5" x 4". They were driven directly by the HP33120A in a continuous wave mode through the frequency range of 0.5 to 200 kHz.

Baseline and post-impact measurement

To show the embedded cure monitoring sensor can be used for vibration measurement, two piezo-actuators on two composite samples were attached with epoxy and one other actuator was attached on another sample with double-sided adhesive tape. Two sensors on each of the three samples were used. The fourth sample was used later for ultrasonic damage detection.

Baseline measurement of the received signal strength was made first for all three samples and repeated. For the taped sample, the repeated measurement was made after detaching and reattaching the actuator. All three samples were then subjected to a 6' - 28 lb impact load per SACMA SRM2 (or Boeing BSS7260) standards. The impact head had a diameter of 1.0", resulting in visible damage. Pictures of impacted parts are shown in Figure 29 for both front and back. The impacts were made at a testing laboratory with a system shown in Figure 30.

After the impacts, measurements were made on these samples using the same sensors and comparing the responses to those prior to the impacts . Table I gives the matrix for the vibration measurements along with the corresponding deviations†. Figures 31 through 33 show the vibrational responses for before and after the impacts of the three samples. The embedded sensors were able to pick up the differences in the composites resulting from the impacts.

Ultrasonic damage detection

The option to detect the damage by using the sensors as ultrasonic transmitter and receiver was also explored. Using one sensor as the transmitter and another two sensors as receivers, ultrasonic waves were propagated in the fourth composite part at 350 kHz. After subjecting the part to the same impact level as above, similar ultrasonic measurement were made again. The impact was purposely done to the perceived wave propagation path. Figure 34 is a photo of the part showing relative positions of the sensors and impact location. Table II lists the matrix for the ultrasonic measurement and Figure 35 gives the received signals for this experiment. Again, the embedded sensors were able to detect the change in the composite part.

† The deviation is calculated using a simple equation: $\sqrt{\Sigma(A-A_0)^2}/\Sigma|A_0|$

Accomplishment

In this task, it was demonstrated that the sensor embedded in the composite parts manufactured in Task 3 can also be used to monitor the vibrational responses of the parts. By using either a separate vibration source or driving an embedded sensor ultrasonically, the structure's vibrational characteristics can be obtained. Furthermore, after subjecting these samples to a specific impact load, the sensors were able to detect the difference in the vibrational responses or the deviation in ultrasonic wave propagation characteristics.

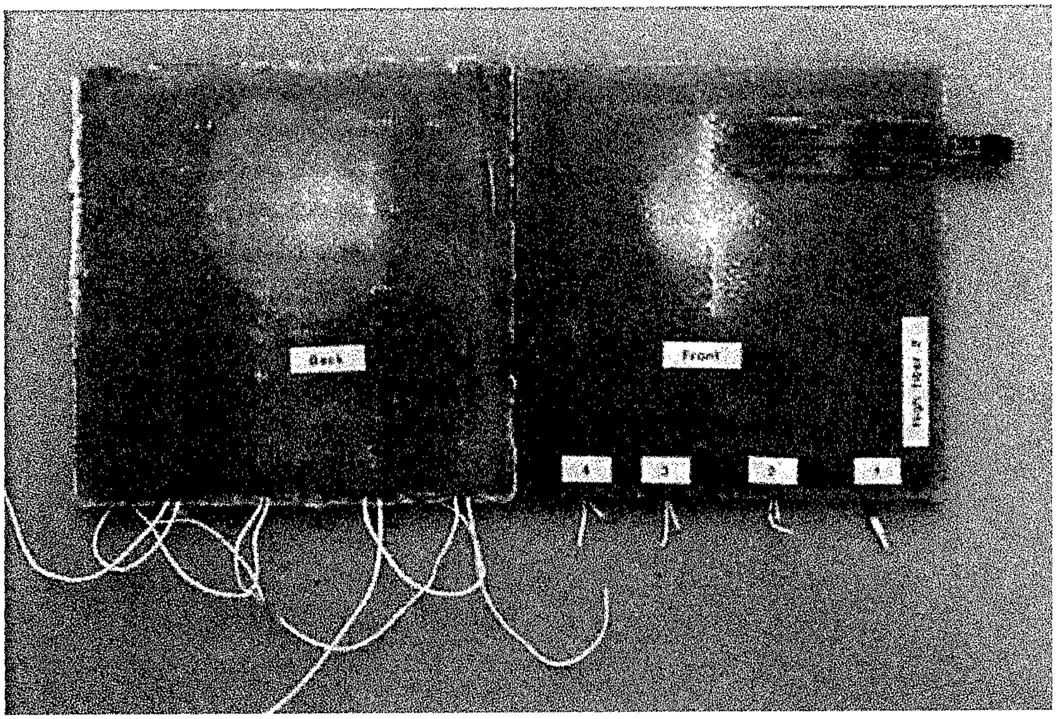


Figure 29. Photo of impacted parts

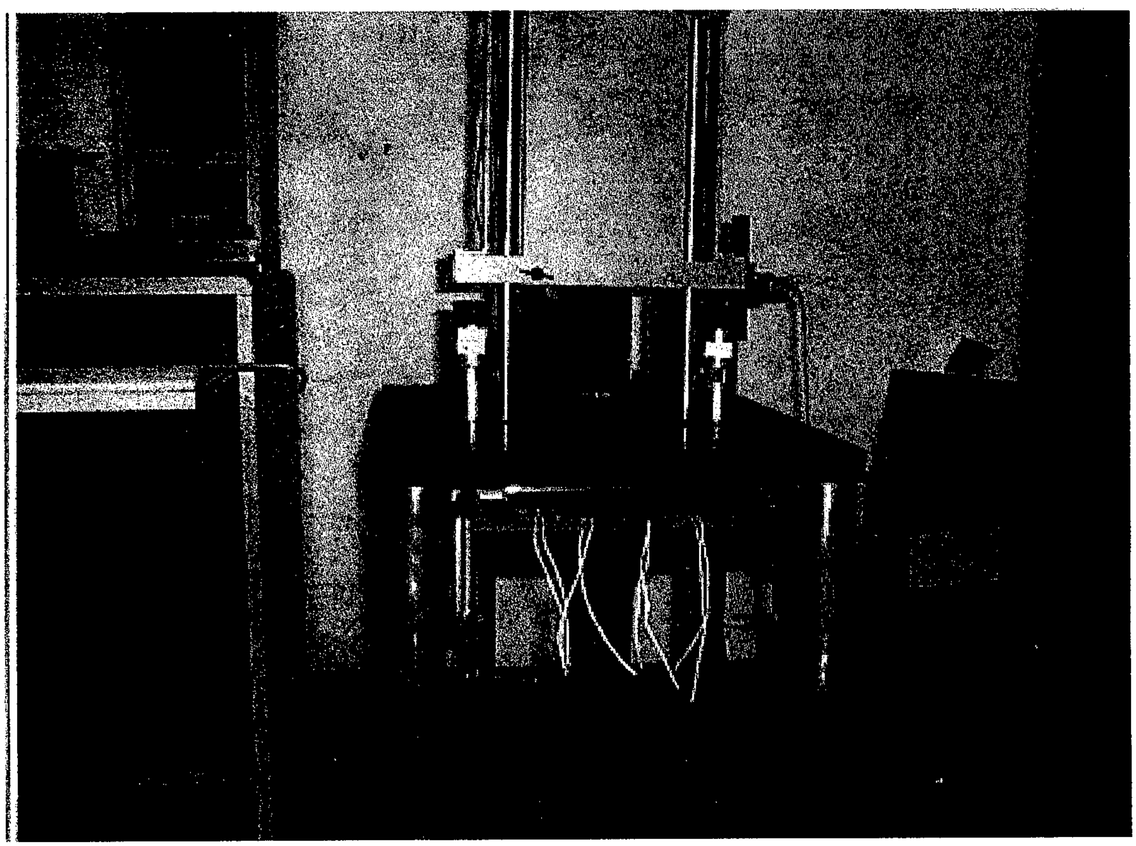


Figure 30. Impact testing system

Table I: Matrix for vibration measurements

Figure #	Part #	Sensor #	Filename	Character	%Deviation[‡]
31	1	5	hf1s5bas.000 (G1)	Baseline	0
	1	5	hf1s5bas.000 (G2)	Baseline (repeat)	0.78
	1	5	hf1s5ocm.000 (G1)	Impacted	3.23
	1	5	hf1s5ocm.000 (G2)	Impacted (repeat)	3.24
	1	3	hf1s3bas.000 (G1)	Baseline	0
	1	3	hf1s3bas.000 (G2)	Baseline (repeat)	0.21
	1	3	hf1s3ocm.000 (G1)	Impacted	3.53
	1	3	hf1s3ocm.000 (G2)	Impacted (repeat)	3.55
32	2	2	hf2s2bas.000 (G1)	Baseline	0
	2	2	hf2s2bas.000 (G2)	Baseline (repeat)	0.27
	2	2	hf2s2ocm.000 (G1)	Impacted	3.85
	2	2	hf2s2ocm.000 (G2)	Impacted (repeat)	3.85
	2	3	hf2s3bas.000 (G1)	Baseline	0
	2	3	hf2s3bas.000 (G2)	Baseline (repeat)	0.25
	2	3	hf2s3ocm.000 (G1)	Impacted	3.44
	2	3	hf2s3ocm.000 (G2)	Impacted (repeat)	3.42
33	3	1	hf3s1bas.000 (G1)	Baseline	0
	3	1	hf3s1bas.000 (G2)	Baseline (repeat)	1.43
	3	1	hf3s1ocm.000 (G1)	Impacted	2.40
	3	1	hf3s1ocm.000 (G2)	Impacted (repeat)	2.68
	3	3	hf3s3bas.000 (G1)	Baseline	0
	3	3	hf3s3bas.000 (G2)	Baseline (repeat)	0.84
	3	3	hf3s3ocm.000 (G1)	Impacted	2.44
	3	3	hf3s3ocm.000 (G2)	Impacted (repeat)	2.48

[‡] The equation used for the computation is given at the bottom of Page 26 and the values are in %.

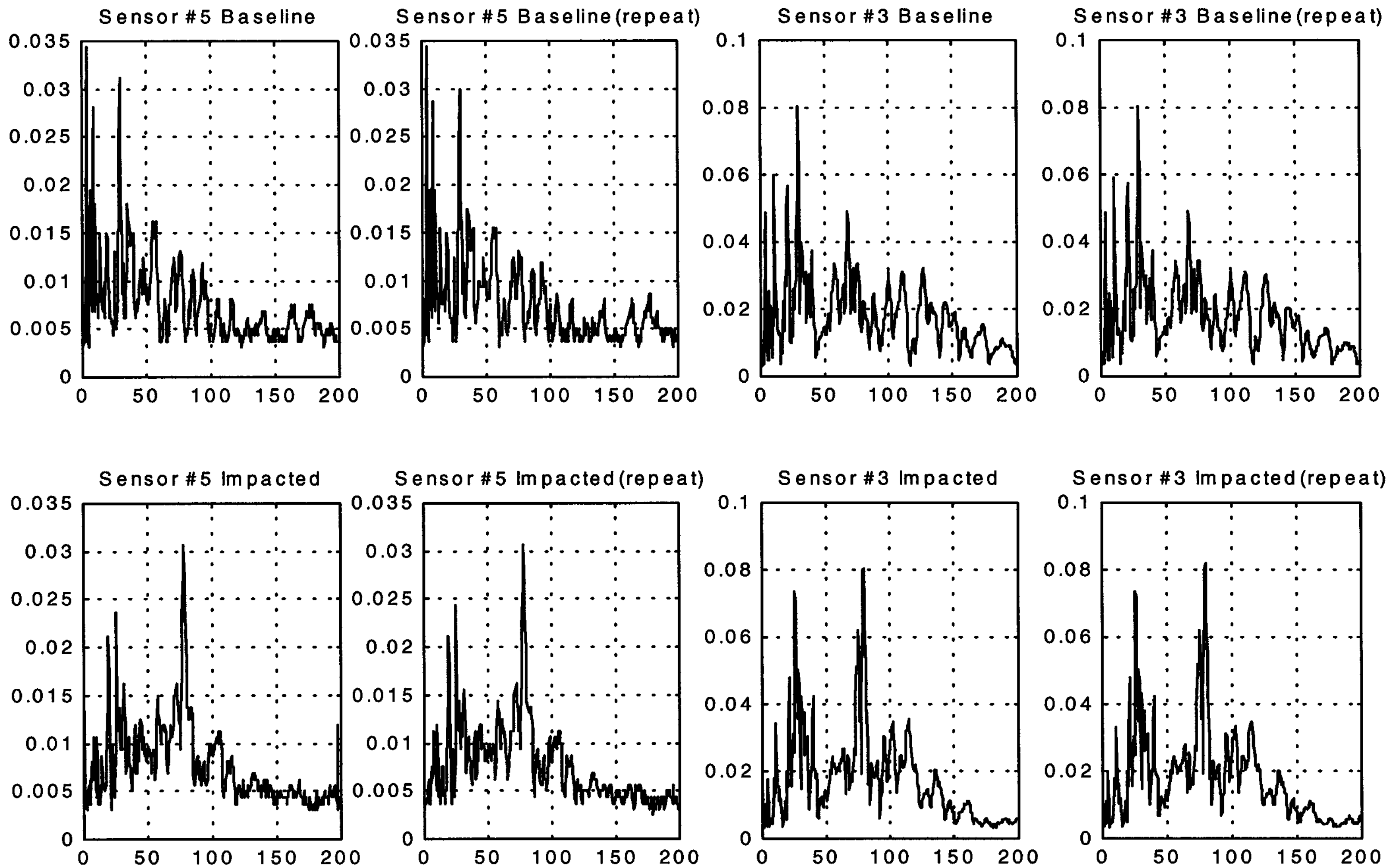


Figure 31. Vibrational responses of composite part #1 (abscissa is frequency in kHz and ordinate is amplitude in V)

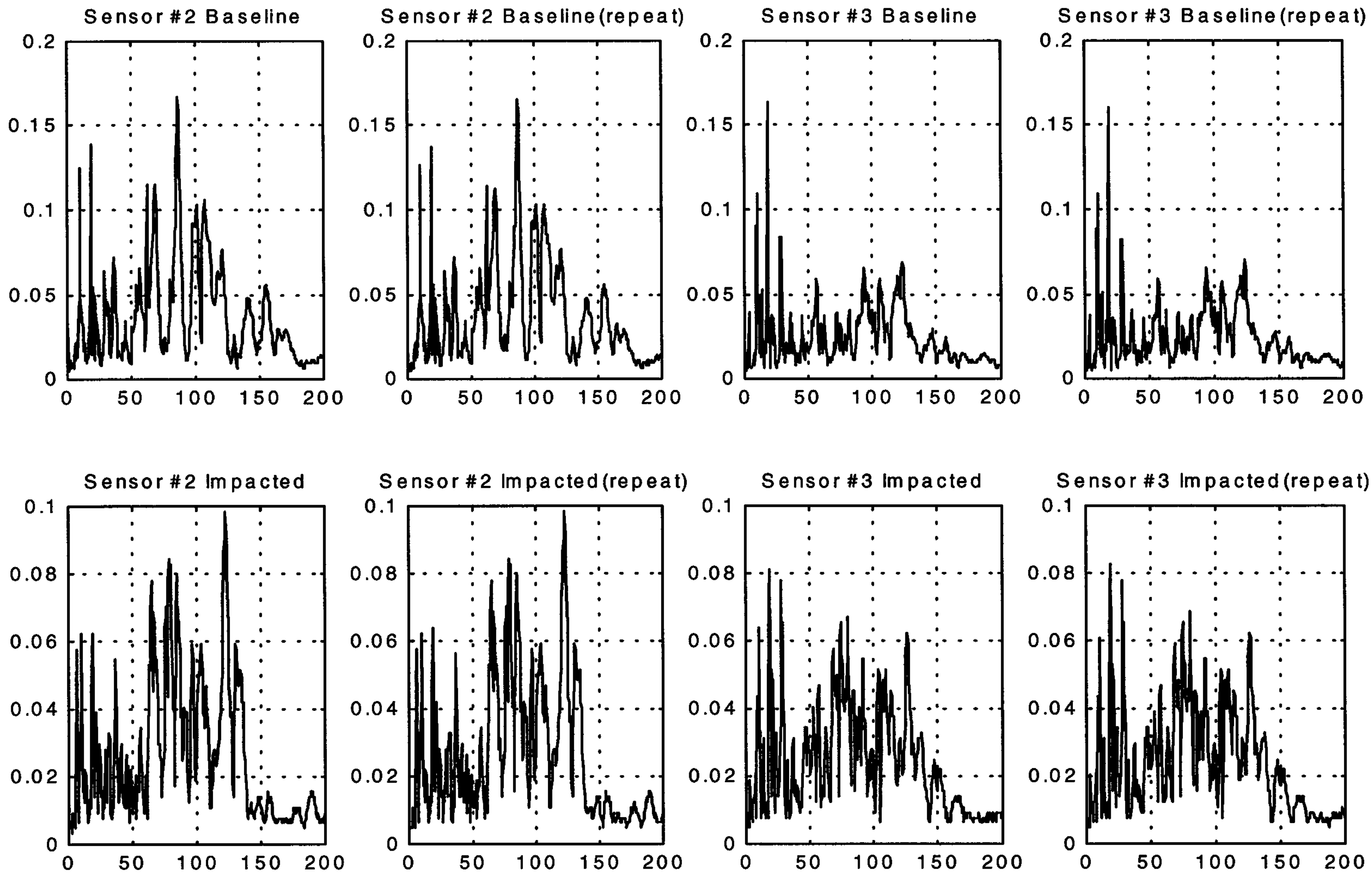


Figure 32. Vibrational responses of composite part #2 (abscissa is frequency in kHz and ordinate is amplitude in V)

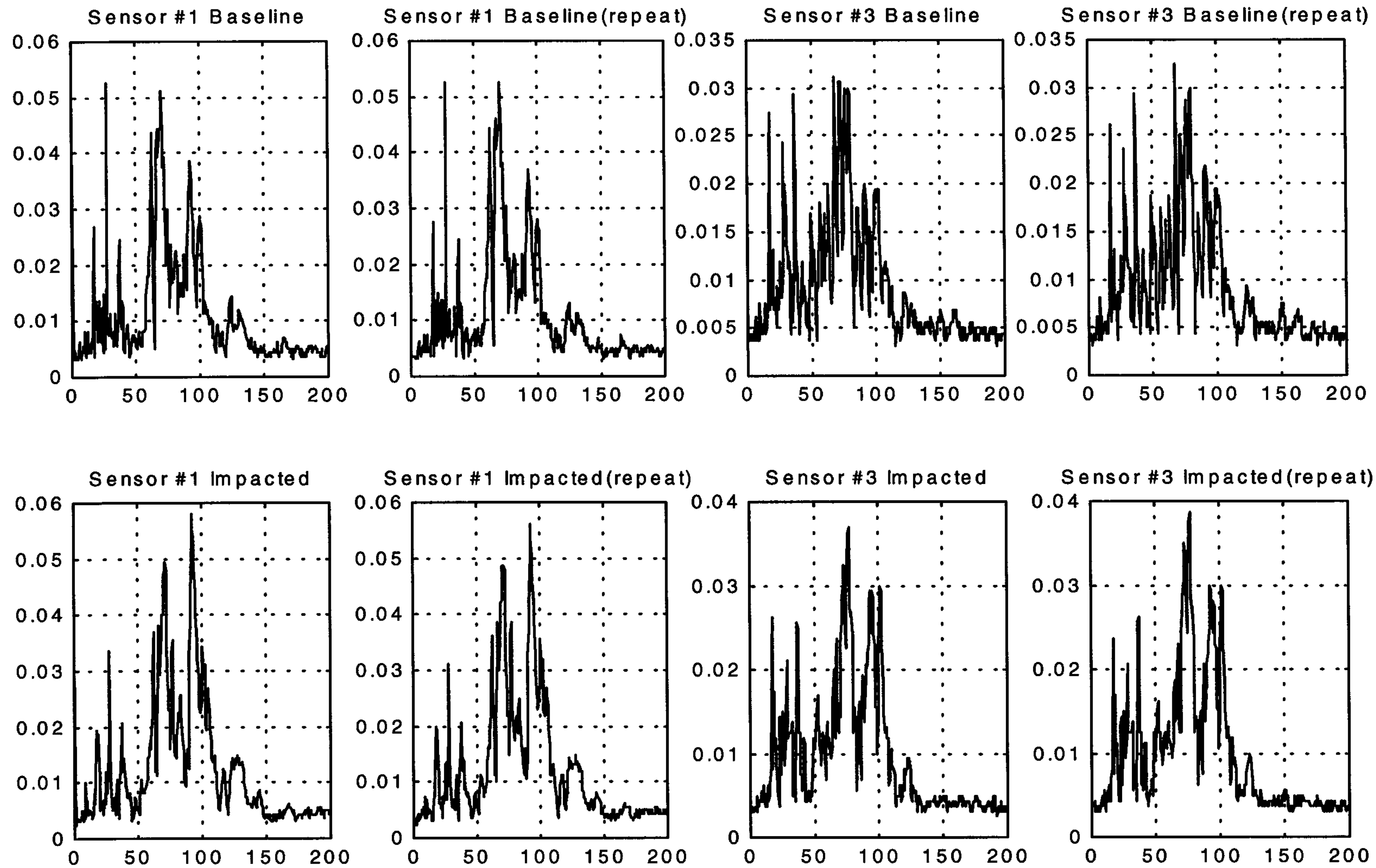


Figure 33. Vibrational responses of composite part #3 (abscissa is frequency in kHz and ordinate is amplitude in V)

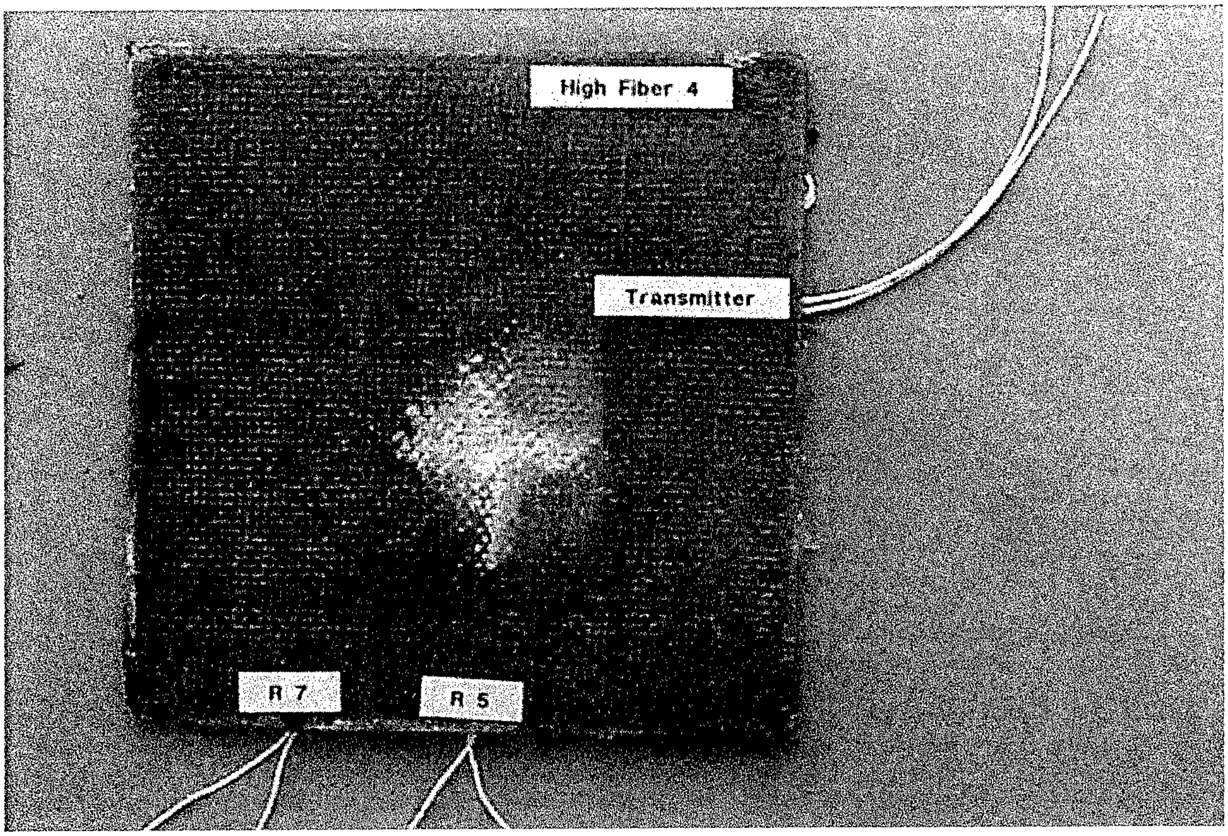


Figure 34. Photo of impacted part used for ultrasonic damage detection

Table II: Matrix of ultrasonic measurements

Figure #	Part #	Sensor # T	Sensor # R	Filename	Character	% Deviation
34	4	2	7	hf4d2r7.AAA	Baseline	0
	4	2	7	hf4d2r7.AAB	Baseline (repeat)	0.83
	4	2	7	hf4d2r7I.AAA	Impacted	4.24
	4	2	7	hf4d2r7I.AAB	Impacted (repeat)	4.33
	4	2	5	hf4d2r5.AAA	Baseline	0
	4	2	5	hf4d2r5.AAB	Baseline (repeat)	0.91
	4	2	5	hf4d2r5I.AAA	Impacted	6.67
	4	2	5	hf4d2r5I.AAB	Impacted (repeat)	6.30

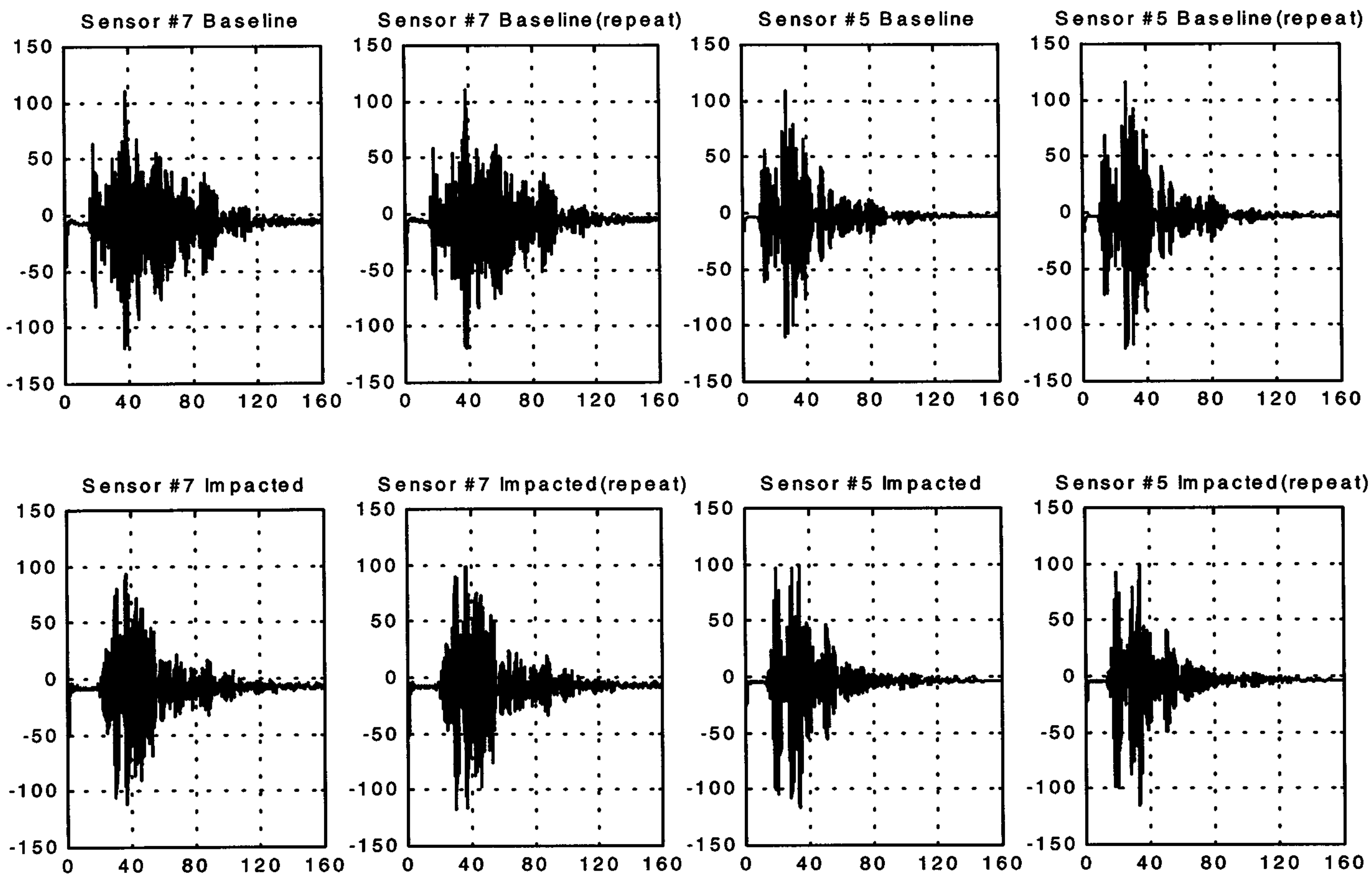


Figure 35. Waveforms for composite part #4 (abscissa is time in μs and ordinate is amplitude in A/D bits)

TASK 5: FINAL REPORT PREPARATION

As the required deliverable, this report is submitted as a final product. Representative experimental data collected in Tasks 1, 3, and 4 were organized and presented in this report. Time-of-flight information not processed in real-time during the experiment was post-processed and included. Conclusion on the technical feasibility of the researched WWG sensor technology was drawn and a tentative plan for Phase II was proposed.

A concise version of the video showing the demonstration process will also be prepared at later time and a copy delivered to the Army technical officer in charge of this project. A presentation to Army research engineers and technical staff can also be scheduled.

III. OVERALL FEASIBILITY AND PROJECT EVALUATION

Technical feasibility evaluation

Phase I of this SBIR program was successfully completed and project objectives were met. This is evident after measuring the result against the criteria presented in the original proposal.

In the original proposal it was stated:

Phase I is considered a success when the following criteria are met:

a) the developed sensor system can clearly identify the times that following occur
   - resin reached the sensor point;
   - resin reached minimum viscosity point;
   - resin becomes completely cured;
b) the developed sensor system can measure the dynamic vibrational response of thick liquid molded composite structures with good reproducibility.
c) the developed sensor system have a realistic chance of practical field implementation.

Experiment results presented in Figures 4, 6, 14, 17 through 20, and 24 through 27 showed that WWG sensors were able to provide the following timing information:

- when the resin reached the sensors
- when the resin reached minimum viscosity point (except when viscosity of the resin did not reduce significantly after being injected into the mold)
- when gelation was in progress
- when resin began to harden and
- when the cure process is effectively complete.

In fact, significant flow/cure information was available throughout the entire cure process in both the amplitude and time-of-flight data. Note that the response curves for all the experiments were very similar for three different types of resins and three different resin introduction mechanisms except unique characteristics at the very beginning of the processes.

Experimental results presented in Figures 31 through 33 showed that the embedded flow/cure monitoring sensors could also be used to make reproducible dynamic vibrational responses of the composite parts. They also showed that impact damages on the composite parts led to deviations in the measured vibrational responses. Furthermore, Figure 35 shows that by using the embedded sensors as ultrasonic transmitters and receivers, the wave propagation characteristics could be measured and damages that occurred in the wave propagation path could be detected.

The researchers felt strongly the WWG sensor developed in this project has great potential and a realistic opportunity for real world application. In addition to the successful demonstration of its technical feasibility in flow/cure/damage monitoring, the following characteristics of the sensor and measurement system support this position:

- Sensor manufacturing cost - - The WWG sensors developed in this project are neither expensive nor difficult to fabricate. The components and equipment needed for the fabrication are generally available off-the-shelf items. The only special order item is the square wire which has about 8 weeks lead time but is not that expensive.

- Sensor manufacturing/performance consistency: After several iterations of design, testing and evaluation, the procedures for sensor manufacturing have been established. Following these procedures was another key factor that made this project successful. Currently, the sensors can be made to operate consistently at 350 kHz and waveforms are consistent in shape with sensitivity deviation less than ±3dB.

- Sensor measurement systems - - The systems developed in this project were geared for a laboratory environment. However, the functionality of this system is straight-forward and special purpose portable instruments can be designed as part of the Phase II effort. Major technical difficulties that cannot be overcome are not anticipated and the cost should be reasonable, particularly if time-of-flight information is optional.

- Sensor ruggedness and suitability for practical implementation - - The WWG sensors are made to be an integrated light structure and are already fairly strong. The ingress/egress are not particularly weak either. Installation does not require any special tools or training. No special handling is required and no health hazardous materials are involved. The mini-coaxial cables are designed for temperatures up to 650°F and their function is not impeded by the sharp turnings or kinks. The jacket of the cable mates well with the vacuum bag seal strips typically used in the SCRIMP process.

- Sensor potential for health monitoring - - There can be a great number of damage detection mechanisms/scenarios developed using the embedded sensors. Two methods were demonstrated here for impact detection. Although not specifically shown here, the embedded WWG sensor can undoubtedly be used as an acoustic emission sensor to passively "listen" for the sound caused by delamination. A combination of active ultrasonic, passive acoustic emission, and controlled vibration techniques may be employed to give real-time combat assessment of the integrity of composite armor structures. An operator of such a system may someday be able to make quantitative statement such as "structural integrity is down 30%".

The researchers at XXsys are very optimistic of the WWG sensor technology and confident in the successes laying ahead.

Overall project evaluation

This project was not completed without overcoming several major obstacles. At the beginning, the project ran relatively smoothly in the neat resin and RTM experiments. Many experiments were designed and conducted to fine tune sensor design and manufacturing parameters, test the hardware, and debug the software. Particularly time consuming was the time-of-flight algorithm development and software implementation for real time operation. Difficulties encountered in this process were considered as normal in the course of the project and were either overcome or by-passed by taking a different approach.

However, significant difficulty was encountered in the SCRIMP experiments. Under the original plan, the SCRIMP experiments were to be performed in collaboration with Seemann Composites, Inc. For logistic reasons, it was decided to utilize the RTM Division of XXsys. However, this created unanticipated problems (and some advantages).

The RTM division of XXsys had never made a SCRIMP part before. Although the technical people had seen the process and read articles about it, actual implementation was more difficult than they thought. Several experiments were carried out before the procedures were in place to make a good part. Another problem was the resin selection. The pot life and viscosity requirements were not fully anticipated. There were also some other related process problems. After several trial and error experiments, the right procedures were established.

Shortly after the SCRIMP experiments were started, the researchers realized the limitation of the round wire sensor design but did not have sufficient time to wait for the square wires to be custom made. As an alternative, the machinist cut the sensor wires out of a 0.025" thick stainless steel plate and contracted a wire company to shape the wire to that shown in Figure 1. Fortunately, the square sensor worked after some fine tuning and the problem associated with the round wire sensor was solved just in time to complete the project. Further, because of the number of iterations in design, testing and fine tuning of the square wire sensors, the decision to perform SCRIMP experiments in-house proved to be correct for rapid evaluation of enhanced sensors.

Another issue should also be mentioned for the vibration study in Task 4. Initially, the parts made by the RTM process were going to be used for the impact study. As it turned out, the high resin content RTM parts made the parts poor candidates for impact studies. Significant damage could be produced with a very small load. With the availability of the high quality SCRIMP parts, more representative impact studies were carried out.

In spite of these difficulties, a unique WWG sensor and measurement technology was developed and the technical feasibility in neat resin, RTM and SCRIMP processes was demonstrated.

IV. CONCLUSION AND FUTURE PLAN

Conclusion

We have developed a novel embedded WWG sensor and measurement technology that can be used for flow/cure/damage measurement of composite parts manufactured by liquid molding techniques such as RTM and SCRIMP. The measurement can be performed in real time for in-process flow/cure monitoring during fabrication and the same embedded sensor can also be used for damage detection and dynamic vibrational response monitoring after the parts or structures are placed in-service. Experiment results obtained in this project have clearly established the technical feasibility of this new low-cost, rugged, easy to implement ultrasonic WWG sensor technology.

Future plan

Based on the success in this project, we are proposing the following for a Phase II effort:

1. Demonstrate the flow/cure monitoring capability: The WWG sensor and the complimentary multi-sensor system will be further validated and demonstrated through the controlled liquid molding of a composite armor demonstration part. Flow/cure information provided by the sensor will be used to intelligently control the manufacturing process. A special sensor measurement system will be configured with software developed for information display and exchange with manufacturing process control system.

2. Demonstrate the damage detection capability: In-service damage detection of the same part will be demonstrated using the same embedded flow/cure monitoring sensor as smart material sensors. A portable measurement system will be built with software and appropriate algorithms developed. The output from this system will be used as input to a structure management system to control and/or correct undesirable mechanical responses.

3. Develop special purpose measurement prototypes: Two single purpose prototypes will be developed for the WWG sensors. One prototype will focus on the flow/cure monitoring for intelligent control of the composite manufacturing process. The other will be designed to perform in-service damage detection and vibration monitoring of the composite structure. Although the main electronics will be similar, substantial differences will be present in the two systems, particularly the functions and user interfaces.

The detailed plan for these proposed activities will be provided in the Phase II proposal upon an invitation from the Army.